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SWIFTS-LA-: AN UNPRECEDENTLY SMALL STATIC IMAGING FOURIER TRANSFORM SPECTROMETER

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INTRODUCTION

SWIFTS [1] spectrometer is already known for its exceptional compactness and robustness. Despite its ability to reach very high spectral resolution such as R>150000, its sensitivity is relatively poor because it exploits single mode waveguides. SWIFTS-LA ("LA" stands for "Large Aperture") is a new device belonging to the generation of Static Fourier imaging spectrometers dedicated to high spectral resolution measurements. Inspired from MICROSPOC and SWIFTS technologies, we will show how this new device exploits stationary waves in high refractive index materials to get a very small spectrometer with a very high angular acceptance. This spectrometer is intimately coupled to infrared or visible detectors making them very stable, compact and sensitive. We will present some results demonstrating preliminary performances and quality of signal reconstruction. Based on these results, we will show how an implementation of SWIFTS-LA can meet at least CARBONSAT specifications in just a few litres spacecraft and how these principles can be implemented for planetary mission imaging spectrometers.[1]

I. DESCRIPTION OF SPECTROMETER PRINCIPLE

A. Basic description

MICROSPOC was described in [2]by S. Rommeluère & al. It is made of a two-waves interferometer glued in front of the detector. Assuming far field conditions, parallel rays coming from infinite are partly reflected by the detector face and the substrate upper face, as illustrated in fig 1, generating an interferogram along the horizontal axis that is detected by the active layer of the detector.

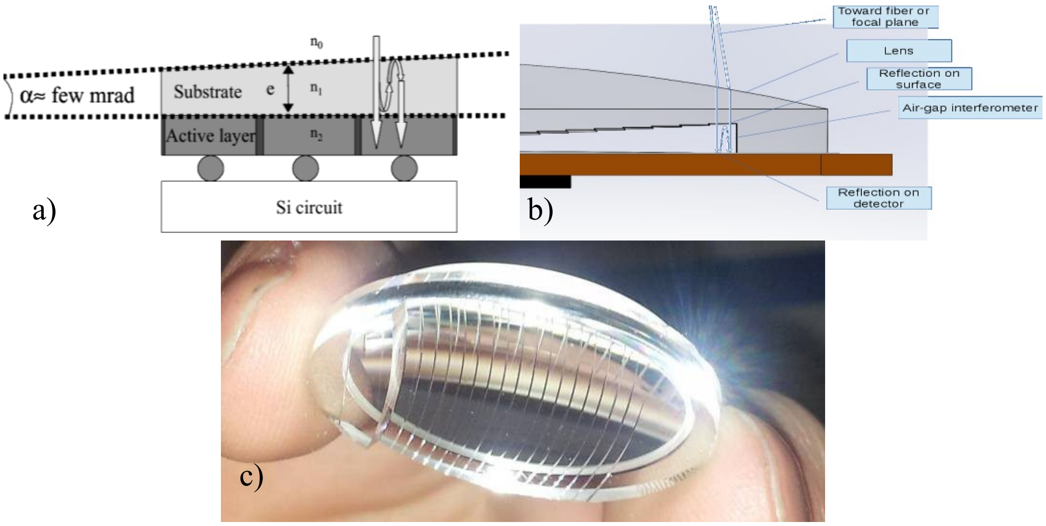

Fig. 1. : **a)** original MICROSPOC structure where the substrate plays the role of interferometer. Here, the detector is a HgCdTe hybrid structure where active photodiodes are coupled to the reading Si circuit. **b)** SWIFTS-LA structure where the interference lays between a stair-step PMMA molded surface and the detector. **c)** the PMMA prism surrounded by a 75mm focal lens. Surfaces are treated with TiO_2 quarterwave layer.

Each pixel of detector sees the point source with an interference state depending on the spacing between the substrate optical thickness and detector. For each pixel of a pixel group under equivalent illumination, a different spacing is used and can be combined to build an interferogram. The schematic figure 2 shows how a detector can be entirely used to make a unique interferogram. Figure 2a gives an example of implementation of

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this spectrometer for one optical fiber. The step prism used in this example allows us to take advantage of 2D detectors to reach high spectral resolution (R>10000) with a very high throughput.

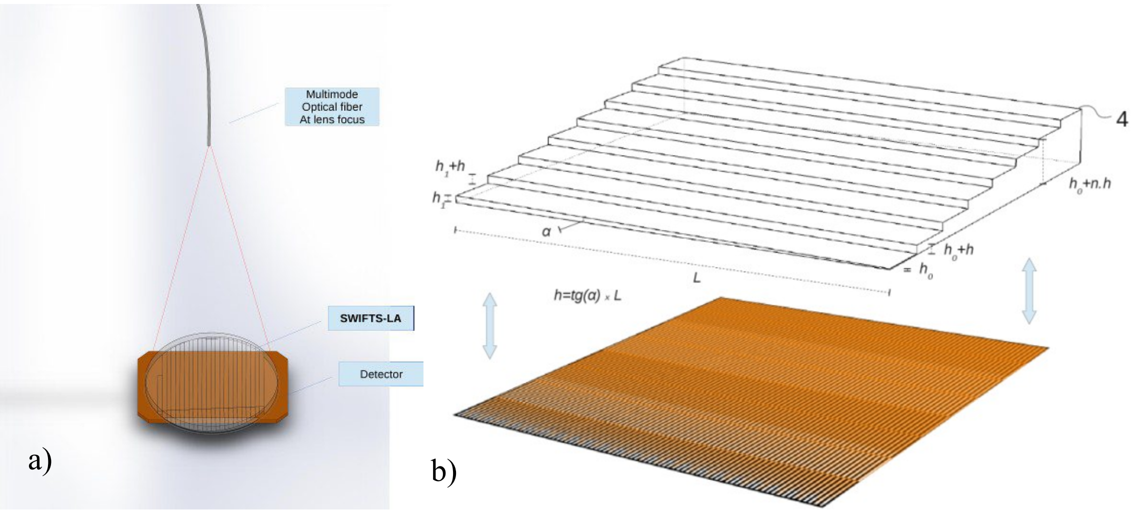

Fig. 2. : **a)** As an example, an optical fiber placed at the focus of the system illuminates the device. **b)** the fringes created by SWIFTS-LA are depicted : along the first inclined stair step, the gap increases from h_0 to $h_1=h_0+h$, the second step addresses a gap from h_0+h to h_1+h, etc, up to the maximum spacing e_{max} defining the spectral resolution of the spectrometer. The h_0 gap corresponds to the minimum spacing between detector and prism which is never 0. This means that the white fringe is not easily observed.

B. Performances and important equations

***Fringes Contrast**:* An approximation of the optimal reflectivity is obtained solving the finesse equation of Fabry-Perot $F = \pi \frac{\sqrt{r}}{(1-r)}$ for F=2, i.e. when the reflectivity is $r = 0.236$ ~ (0.25 in [2]). For this reflectivity, the contrast of the fringes is nearly 60% over the 80% of entrance light which is detected. Then, the efficiency of such spectrometer is 0.6x0.8 ~50%, the noise must be calculated on 80% of flux.

This reflectivity can be obtained by three methods:

- ✓ a metallic coating like aluminium, gold or silver
- ✓ a dielectric transition between two materials n_1 and n_2 with $n_2=2.89*n_1$ (like glass on silicon)
- ✓ introducing a λ/4 layer such as TiO_2 on glass and on the detector

In the presented prototype spectrometer, the maximum fringe contrast is limited to 20% because only one quarterwave layer of TiO_2 has been deposited on the PMMA prism.

***Spectral Resolution**:* The maximum spectral resolution is given by the maximum substrate spacing used (e_{max}). for a maximum physical spacing, the apodized spectral resolution is :

$$R(\sigma) = \frac{\sigma}{\delta\sigma} = \frac{e_{max}}{\lambda} \tag{1}$$

In the prototype spectrometer, the spectral resolution is R=3850 at 671nm ($\delta\lambda=0.176$ nm) which is equivalent or better to the ChemCam spectrometer onboard the Mars Science Laboratory Rover.

***Spectral bandwidth**:* The spectrometer samples continuously the fringes from optical contact to maximum spacing. To limit the effect of pixel spatial filtering, each consecutive pixel must sample ¼ of fringes at the shortest wavelength. The bandwidth is mainly limited by the detector detectivity and the fringe contrast. A single quaterwave layer of TiO_2 over a glass with 1.5 refractive index ensures more than 50% of contrast over one octave (400 to 800 nm for example).

In the presented spectrometer, the spectral sampling is ΔL=250nm and bandwidth is 500-1100nm (9300 to 20000 cm^{-1}).

***Signal acceptance**:* Depending on the maximum spectral resolution that we want to reach, the size of the source through the imaging optics must be limited. Gillard [3] has derived the equations that link the maximal angular size of the source and the spectral resolution condition permitting the system to accept a maximum of optical *étendue*. To simplify we can use the following formula related to the telecentric f/N condition. :

$$R_{max} = 2(2 \times n.N)^2 \tag{3}$$

Where R_{max} is the maximum spectral resolution, n the refractive index of the medium filling the space between the two faces of the interfering prism (here air spaced $n=1$), N an aperture number defined by the ratio between the lens focal length and the source diameter ($d=f/N$).

In the presented spectrometer, full spectral resolution is achieved up to a 3.5 mm fibre core seen at lens focal 75mm which corresponds to R=3850Such a size of fibre allows us large collecting power. This collecting power is even larger when the substrate index is higher as it is described in [3].

II. SPECTROMETER TEST:

A. prototype assembly

A first prototype has been built in the visible range using a 30mm diameter PMMA plate with a 70nm TiO_2 coating to optimize reflection from 600 to 1100nm. A coated 75mm focal length BK7 planoconvex is glued to the plate in order to collimate the optical fiber. A SiN passivated e2V CMOS detector with no coating has been used. The specular reflection is not sufficient to insure maximum contrast of fringes limiting the fringe contrast to 20%.

Fig. 3. : SWIFTS-LA, the 140g whole spectrometer detector allowing us to acquire digital images on an USB2 interface. The spectral resolution is 176pm at λ=762nm meeting the 200pm CARBON-SAT specification for Oxygen-B band.

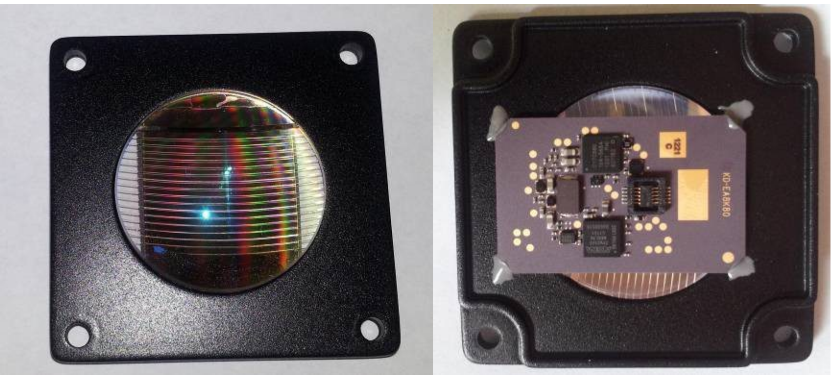

Fig. 4. : The main part of the spectrometer consists in the lens glued to the detector surface. **a)** Front image of SWIFTS-LA **b)** The embedded electronic of CMOS detector allowing to output digital image over USB2 interface. The weight of the spectrometer is less than 18 grams.

B. Data acquisition and reduction

The detector is read using a dedicated acquisition software saving FITS format data. Fig. 5 shows raw data for laser diode light. The fringes appear as very small vertical lines.

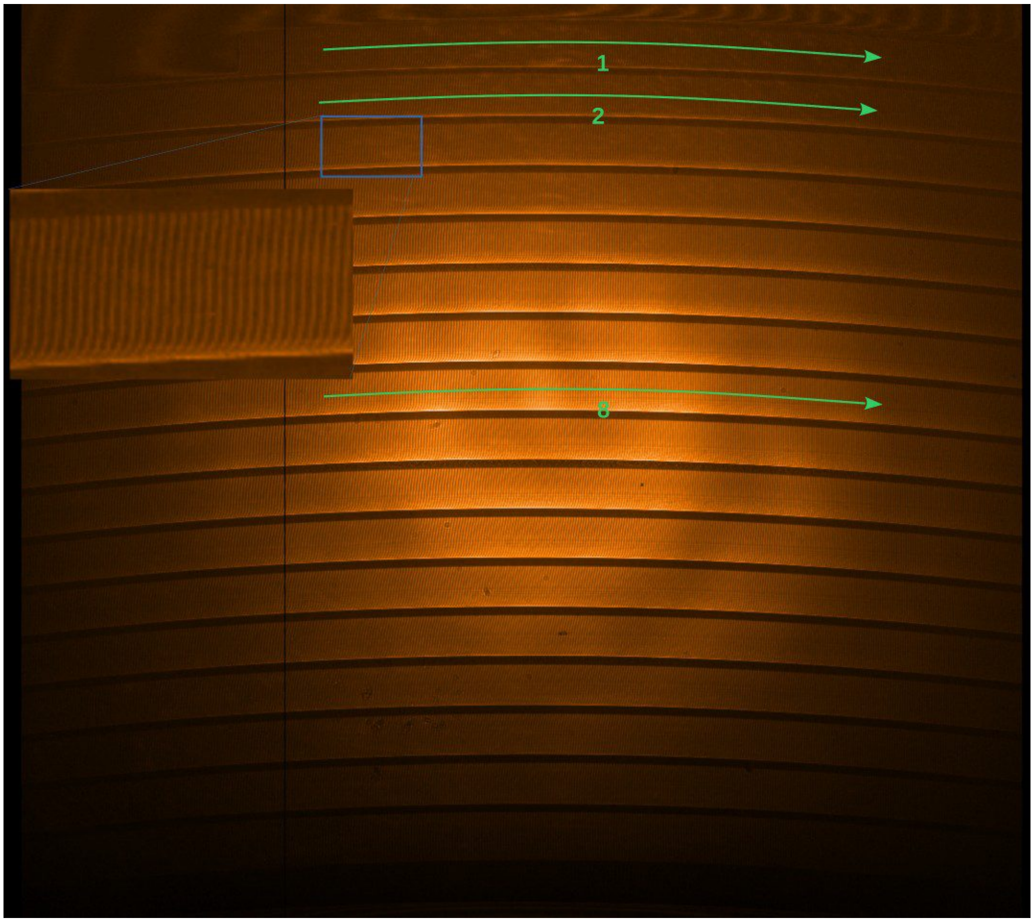

Fig. 5.: Image of distributed feed back laser diode at 852nm. A zoom window shows fringes appearing as narrow vertical patternstarting at upper left corner of image along curved steps. Cavity spacing increases by h=64 µm at each step. The data extraction follows the curved arrow lines along each 17 steps to extract fringes and associates each pixel to a dedicated spacing. Around 40 pixels along a vertical line contribute to sample a fringe.

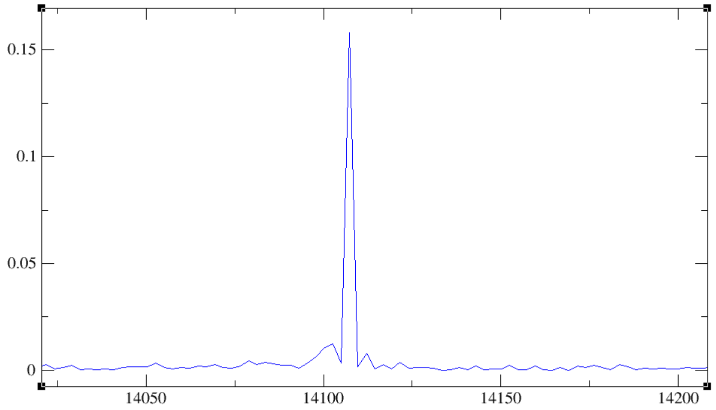

Fig. 6. : spectral reconstruction of a 852nm laser diode with 4cm^{-1} resolution.

In a second experiment, we studied an Argon gas lamp, as shown in figure 7.

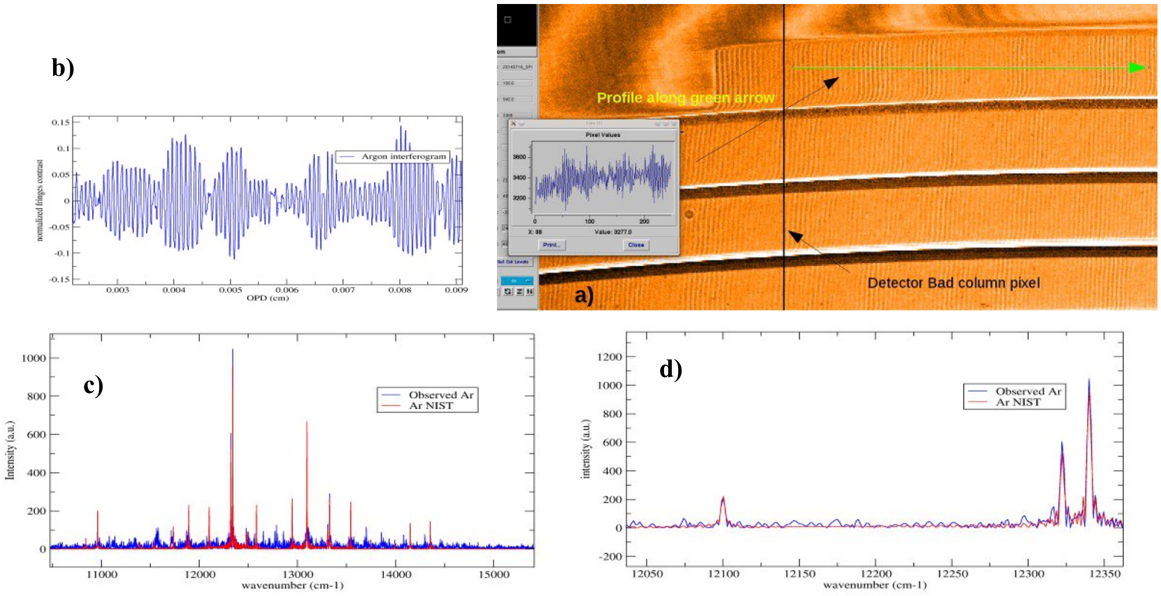

Fig. 7. : **a)** Zoom on image obtained with an argon lamp. A cut is displayed along the green line to show the raw interferogram. **b)** The same interferogram after data reduction **c)** reconstructed spectrum superimposed on a simulated spectrum from National Institute of Standards and Technology database **d)** zoom on several lines

TOWARD SPACE APPLICATIONS

A. Visible domain: LIBS and Raman spectrometry

SWIFTS-LA inherits from MICROSPOC spectrometer specially developed for infrared applications with spectral resolution limited to R=(wide size in pixel/3) (R~100). The major improvement of SWIFTS-LA is to use a larger number of pixels to sample the interferogram with a better use of 2D detectors (R up to 20000, $\delta\lambda$=0.046 nm at 850nm). This technique can be also applied to the visible and UV ranges with a huge collecting power advantage at high spectral resolution compared to classical spectrometers such as ChemCam (0.3 nm at 850nm).

The presented prototype has not been optimized for high spectral resolution in the UV domain but in the same volume and weight, we can build a visible range spectrometer with performances required by ExoMars.

B. imaging the NIR domain: CARBOSPOC

The principle of SWIFTS-LA can be used inside an integral field spectrometer where the field of view is imaged over a collection of small spectrometers. An arrangement of lens and prisms must be found to optimize both detector size and spectral resolution. In CARBOSPOC an imaging spectrometer configuration using a 80x80 SWIFTS-LA can be made using Sofradir 640x480 SWIR detector. Performances are calculated for a 800km heliosynchronous orbit spacecraft, each of the 80 2x2 km field of views are observed 80 times (the instrument layout is not depicted here for confidentiality reasons).

performances for B2 channel

- dimension of the optical instrument including telescope : 150x50x50mm
- total field of view : 160x2km
- elementary field of view : 2x2 km
- spectral resolution = 278 pm (1.4 mm thick, Silicium refractive index 3.4)
- spectral range = 1590-1675 nm
- detector = 640x480 25µm pixels, 77K Stirling cooled;
- exposure time : 80x0.3s
- number of photons coming from a 2x2km elementary field of view : $3.58\ 10^9$ photons
- general throughput : 50%
- SNR = ~155

CONCLUSION

We have presented the first prototype of a spectrometer with very promising performances in the visible and near-IR. The actual design can be optimized using more sensitive detectors such as the new generation of CMOS with better readout noise. A 60% fringe contrast is attainable with a specific detector coating not yet available. The infrared version should be developed and tested to assess its performances.

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REFERENCES

[1] Le Coarer, E., Blaize, S., Benech, P., Stefanon, I., Morand, A., Lérondel, G., ... & Royer, P. (2007). Wavelength-scale stationary-wave integrated Fourier-transform spectrometry. Nature Photonics, 1(8), 473-478.

[2]Sylvain Rommeluere ; Nicolas Guerineau ; Joel Deschamps ; Eric De Borniol ; Alain Million, et al. "Microspectrometer on a chip (MICROSPOC): first demonstration on a 320x240 LWIR HgCdTe focal plane array", *Proc. SPIE 5406, Infrared Technology and Applications XXX, 170* (August 30, 2004); doi:10.1117/12.542040; http://dx.doi.org/10.1117/12.542040

[3] Gillard, Frédéric; Ferrec, Yann; Guérineau, Nicolas; Rommeluère, Sylvain; Taboury, Jean; Chavel, PierreGillard et al.(2012)] 2012 *JOSAA*..29..936G

[4] Bianco, P.; Pisani, M., Zucco, M., "High throughput, compact, imaging spectrometer", *International Conference on Space Optics Rhodes*, Greece 4 - 8 October 2010

[5] S. Rommeluère, N. Guérineau, R. Haidar, J. Deschamps, E. De Borniol, A. Million, J-P Chamonal and G. Destefanis, "Infrared focal plane array with a built-in stationary Fourier-transform spectrometer: basic concepts", Opt. Lett. 33, pp 1062-1064 (2008).

[5] M. Fendler, G. Lasfargues; S. Bernabé; G. Druart; F. de la Barrière, S. Rommeluère, N. Guérineau, N. Lhermet, H. Ribot « Integration of advanced optical functions on the focal plane array for very compact MCT-based micro cameras », SPIE Vol. 7660 (May 2010).