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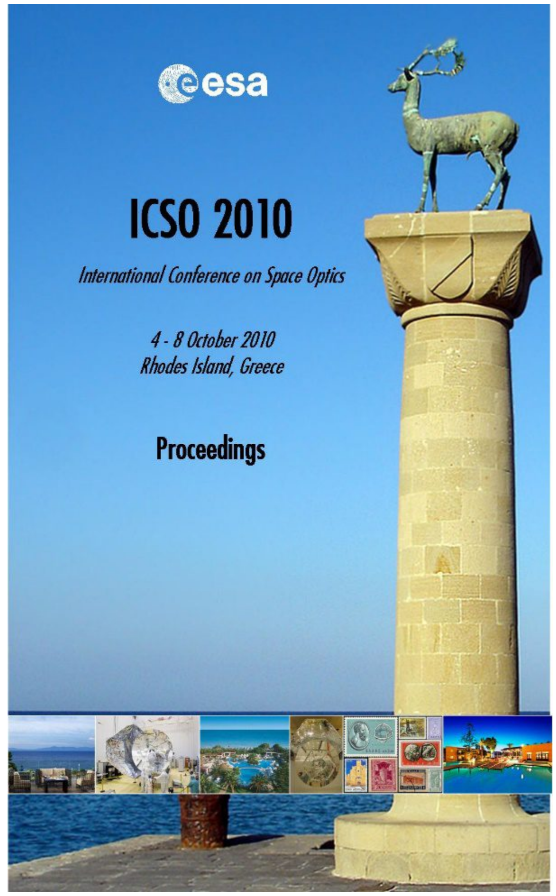

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SWIFTS : ON-CHIP VERY HIGH SPECTRAL RESOLUTION SPECTROMETER.

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ABSTRACT

The size and the weight of state of the art spectrometers is a serious issue regarding space applications. SWIFTS (Stationary Wave Integrated Fourier Transform Spectrometer) is a new FTS family without any moving part. This very promising technology is an original way to fully sample the Fourier interferogram obtained in a waveguide by either a reflection (SWIFTS Lippmann) or counter-propagative (SWIFTS Gabor) interference phenomenon. The sampling is simultaneously performed the optical path thanks to "nano-detectors" located in the evanescent field of the waveguide. For instance a 1.7cm long waveguide properly associated to the detector achieves directly a resolution of 0.13cm-1 on a few centimetre long instruments. Here, firstly we present the development status of this new kind of spectrometers and the first results obtained with on going development of spectrometer covering simultaneously the visible domain from 400 to 1000 nm like an Echelle spectrometer. Valuable technologies allows one to extend the concept to various wavelength domains. Secondly, we present the results obtained in the frame of an activity funded by the European Space Agency where several potential applications in space missions have been identified and studied.

I SWIFTS PRINCIPLES & STATUS

A. Principles

The Stationary-Wave Integrated Fourier Transform Spectrometer (SWIFTS) encapsulated a concept for on-chip spectro-detection described and demonstrated by several papers [1][2]. The detection is achieved along a standing wave that lies in a waveguide by probing the interferogram. Based on this concept a motionless device is able to probe the spectral information of the incoming signal. Several implementations have been investigated in several electromagnetic domains (Visible, Infrared and millimetric).
For all of these cases the basic principle is the same: a set of scattering dot/detectors extracts only a small fraction of the guided energy. The pitch of the detector set will match a convenient sampling of the standing wave, preferably more than 2 samples per fringe. The detectors must be smaller than a sixth of one fringe accounting the refraction index of the propagating material : $d_s < \lambda_{\min}.n_{eff} / 6$

SWIFTS Lippmann
In a first mode named SWIFTS-Lippmann (see Fig. 1a,b), the electromagnetic radiation is coupled into a wave-guide ended by a mirror. The standing waves form the interference pattern along the wave-guide, with its central black fringe locked onto the mirror. It provides a Lippmann interferogram starting by a dark fringe. This mode gives access to the spectra of the incoming light, like for a Fourier Transform Spectrometer.

SWIFTS Gabor
In a second mode named SWIFTS-Gabor (see figure 1b,c), the electromagnetic radiation is split in two equal parts. These two parts are injected in counter-propagative scheme from the two extremities of a waveguide. In this scheme the two arms of the resulting interferometer are accurately balanced by construction in order to place the central fringe at the center of the detection zone. The resulting standing wave forms a Fourier interferogram along the guide. In this mode, in addition to the spectra of the incoming electromagnetic radiation, one has also access to its phase thanks to a measurement of the central fringe displacement with respect to the theoretical central fringe location. A design based on this mode is able to achieve interferometric metrology between the two arms of a convenient setup thanks to a measurement of the central fringe position.

Presently the ideal case (*i.e.* oversampling of the interferogram in the meaning of the Shannon criterion) is only achieved for the radio frequencies [3] domain where sub-wavelength detectors are available. In the optics domain the detection is achieved using nano-detectors with a pitch larger than a wavelength scale.

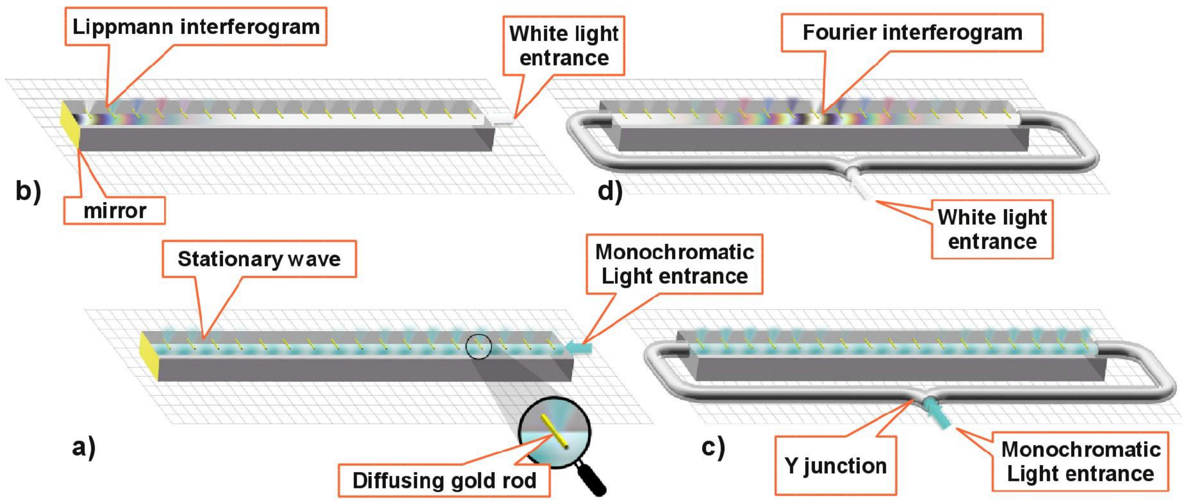


Fig. 1. SWIFTS principles Nanodetectors are placed in the evanescent field of the waveguide. Each detector samples a small part of the flux over a distance smaller than the fringe size. For polychromatic input light, the resulting superimposition of stationary waves lead on to a Fourier interferogram sampled by the set of nanodetectors. The lower 3D artist views present the corresponding SWIFTS devices for colored entrance light and the resulting interferograms.
Left: a) SWIFTS Lippmann principle. The forward propagating optical field coupled in the waveguide is reflected on the mirror at the waveguide end. An interference is made with returning field forming a stationary wave. **b)** The stationary waves are locked on the mirror leading to the so-called Lippmann interferogram starting by a black fringe.
Right: c) SWIFTS Gabor principle. The two coupled waves propagate in the waveguide in counter-propagative mode. **d)** The stationary waves are centered on the zero optical path difference location giving an access to the measurement of the interferogram phase.

B. Performances

In first approximation, SWIFTS can be considered as a FTS, main characteristics are comparable to those of a Michelson interferometer. The mirror replaces the FTS beam splitter with a very good spectral coverage. The number of used detectors is minimal because only one side of the interferogram is sampled, the mirror defining itself the ideal null value for the dark fringe. The measurement stability only depends of temperature that can be achieved independently.

Spectral resolution
Because in SWIFTS the interferogram takes place in a material medium (waveguide) we have to take in account the effect of the index of refraction.

$$R_{unap} = 2n\frac{1.67\delta_{\max}}{\lambda}; R_{apod} = 2n\frac{1.10\delta_{\max}}{\lambda} \quad (1)$$

For instance in the case of a 1.7 cm long device, an apodized resolution of 89600 is achievable at 635 nm with a refractive index of n=1.5. This corresponds to $0.17 cm^{-1}$ spectral resolution

Efficiency (mono-mode and multi-mode)
This approach based on detection in the evanescent field, allows proper sampling of the interferogram using small size detectors in comparison to one sixth of the wavelength of the guided light. It has been shown that an ideal positioning of the wires of the SWIFTS arrangement permits the spectrometer to build an interferogram using 74% of the incoming photon in waveguide [1,3]. First prototypes provide a proper demonstration of the principle at various wavelengths. The above mentioned publication presents a measured spectrum over an 80 nm range (1.5µm - 1.58µm) with a 4 nm resolution.
The SWIFTS Lippmann with spatial multiplex has also the advantage to increase the optical etendue. Thus for non punctual object SWIFTS Lippmann is more sensitive.

Spectral coverage (Shannon, Detection efficiency and transmittance of wave guide …)
As for the spectral resolution we have to take in account the index of refraction:

$$\sigma_{\max} - \sigma_{\min} = \frac{1}{4n\Delta L} \qquad (2)$$

Where ΔL is the distance between two nano-detectors or scattering centers. Because we still using detectors with a pixel pitch larger than wavelength, the attainable spectral range is only 100cm^{-1}. To overpass this strong limitation and take benefits from matrix detectors for which we can set 256 parallel waveguides enlighten with the same source. The common mirror placed on the last surface of the substrate is tilted with a small angle in order to gentle shift sampling dot's place in interferogram. This permits to have a complete Shannon sampling giving an access to the whole domain spectra accessible by detectors.

SNR
For SWIFTS the SNR calculation is the same as for a FTS.

Impact of the light polarization
The diffusion by scattering nano-dots method used to sample the interferogram is sensitive to the polarization of the light. The nano-scattering centres have a different power of diffraction for the TM (Transverse Magnetic) mode and the TE (Transverse Electric) mode (the TM mode is more efficiently diffracted). A solution for avoiding this problem is to separate the polarizations before introduction in waveguides, rotating one polarization and then to inject them in another adjacent waveguide.

C. Some recent developments

To simplify full demonstration of SWIFTS, we have choose to make a system using well known silver exchanged glass waveguides extended in visible domain. Some gold rods are placed at the glass's surface by an e-beam written lift-off process. As it has been done in previous publication [1,2], we record images with a classical microscope. An delay line permits us to scan fringes between to successive 3µm dots position. The recovered spectra is shown in Fig 2.

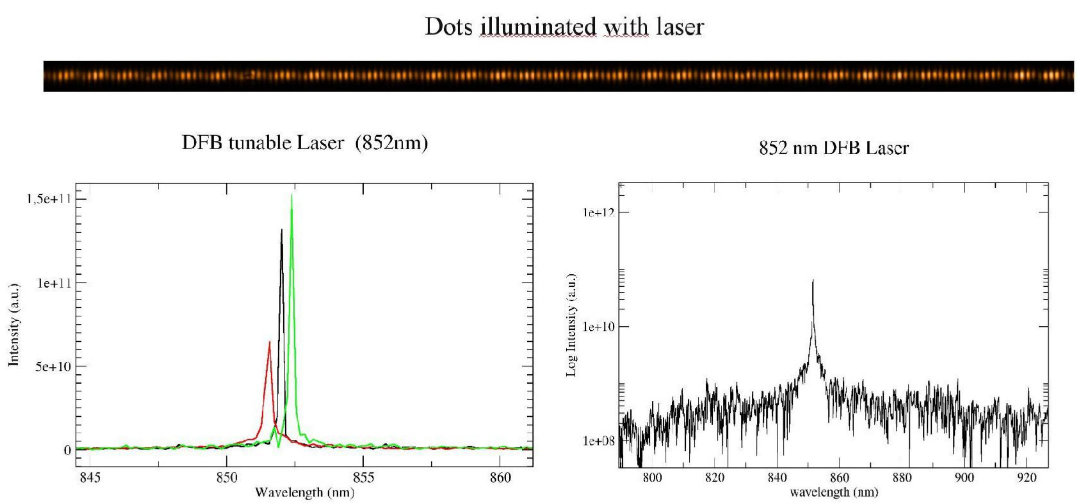


Fig. 2. Visible SWIFTS tests at 852nm : in the SWIFTS 400-1000 framework, we have developed special single mode waveguides on the 400nm to 1000nm domain. Upper : a enlargement of a laser illuminated waveguides covered showing 256 over 512 dots placed every 3µm in the evanescent field. Fringes appears like a Moiré figure. The measured 220 pm spectral resolution is compatible with predictions. A logarithmic representation used in spectra analyzers shows the quality of the recovered peak.

The SWIFTS 400-1000 project propose to glue the glass plate containing the 256 waveguides directly on visible CCD detector to build the spectrometer covering in one shot all the visible domain from 400 to 1000nm with a 0.2cm^{-1} apodized spectral resolution. The light is coupled to system by a fiber bundle system permitting one to use a feeding 25µm diameter core fiber. The fig 3. shows a non-running mockup of the developed system.

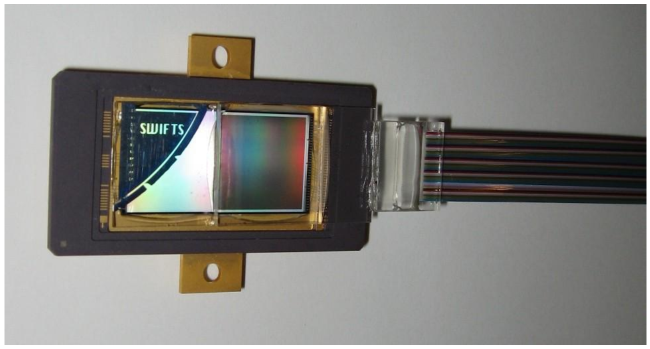


Fig. 3. SWIFTS 400-1000 mockup: A 1K frame transfer CCD is surrounded by a glass plate containing parallel waveguides and diffusing dots is fed by optical fiber bundle. A 0.2cm^{-1} apodized spectral resolution is foreseen.

III. SWIFTS for SPACE APPLICATIONS

In a recent work funded by European Space Agency [5], we have analysed strengths and weakness of SWIFTS for its use in space environment. Even if this concept can be used for lot of applications, we identified and analysed five domains where SWIFTS can be proposed with state of art detector technology such CCD, CMOS, hybrid MCT infrared detectors or SSPD (Superconducting Single Photon Detector [4]).

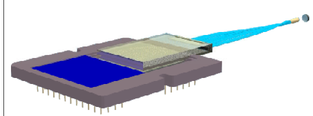
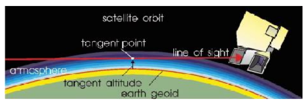
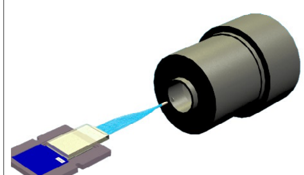
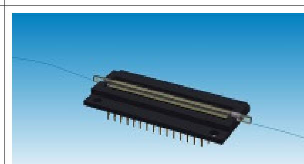
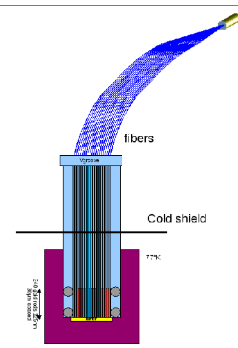
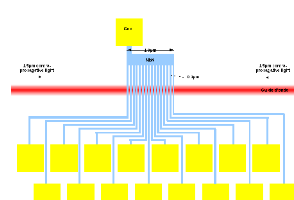
Weight and volume
The intrinsic volume and weight of SWIFTS based optical instrument can be 10^6 times less than classical instrument. For instance an hybrid 2K×2K MCT Hawaii Teledyne detector cover by silicon array of waveguides is equivalent for spectral resolution to the 0.035cm^{-1} MIPAS FTS aboard ENVISAT, Nevertheless, to properly estimate weight and volume we must include all feeding optics, cryogenic, electronic and computer associated to instrument which remain constant.

Field of view
As it is developed for SWIFTS 400-1000 project (see Fig 3.), we have considered SWIFTS built with a set parallel waveguides joined to a matrix fed by an image slicer. This permits one to adjust the right number of pixels to properly sample the dedicated spectral domain according to the generalized Shannon's theorem. Each single mode waveguides intrinsically defines an elementary optical *étendue* of λ^2, total acceptance of the system is equal to the number of waveguides × λ^2 , then the diameter of the entrance optics define the field of view. A 256 waveguide SWIFTS in visible spectral domain on a LEO orbit can observe a field of view of 20 meters at background with a 40 cm diameter telescope.

Radiometry
As a consequence of the wavelength depending small acceptance of SWIFTS, with today noisy infrared detectors, the sensitivity expressed in NESR remain greater than 2000 nW/cm^2/sr/cm^{-1} at 10 µm , and 100 times higher at 1µm. SWIFTS spectrometer cannot compete actually for ultimate detection on large acceptance angle necessary for detection of emission line in earth atmosphere. Inversely, the new generation of high dynamic APD detectors [6] should improve SWIFTS to reach this very demanding goal.

TRL
The SWIFTS concept has already proved in laboratory and published. The aim of the SWIFTS 400-1000 framework is build a running system with well known technologies for background use. The assembly tests should occur next months.

The following table summarizes this study.

Mission	Scope	SWIFTS	Performances summary
Planetary exploration (rover) : LIBS-RAMAN	Associated to LIBS, Identify elemental composition of soil or rocks. An improved spectral resolution permits one to directly get the isotopic composition for some elements. As it was proposed fo Exomars, the same spectrometer can be used in Raman version to identify more complex organic molecules with 0.2cm-1 resolution from 20 to 4000cm^{-1} .	 SWIFTS 400-1000	Weight 360g Volume : 0,216 litre Consumption : 7.4W Spectral range from 400 to 1000 nm Resolution : 0.2 cm^{-1} SSNR= 60 emission spectra in 0.1 s TRL level 4
Planetary or earth observation: Limb Sounding Visible or Infrared High Spectral resolution spectrometer :	 Atmosphere analysis, looking sun or stars through planetary atmosphere thanks to a comparative analyze of molecular lines with the best spectral resolution in 5 spectral band	 Infrared hydride MCT matrix based SWIFTS	Instrumental volume 60l 5 Hawaii II RG detectors 10 cm optics on Mars 40 cm on Jupiter 0.04cm^{-1} spectral resolution SSNR > 300 without atmosphere NESR (nW/cm^{2}.sr.cm^{-1}) 2000→ 30000 TRL level 3
Space Metrology	Small simple compact and stiff Gabor solution to gain accuracy in metrology for gravitational and astrometric observation	 Linear CCD SWIFTS-Gabor mode	Precision < 1 picometer Laser measurement in 1 second. White fringe tracking capability TRL level 4
Earth or planetary Observation Atmosphere sounding	25 parallelized SWIFTS achieve 1250km atmosphere sounding observation with 25km spatial resolution on ground and 0.25 cm^{-1} spectral resolution in LEO orbit 	 cooled MCT detector with chalcogenide SWIFTS fed by fibers or µlenses .	Instrumental volume : 25 litres Spectral resolution : 0.25cm-1 Spectral Band : 3.62 – 5.00 µm : SSNR*= 47 5.00 – 8.26µm : SSNR=200 8.26 – 15.50 µm : SSNR=1000 TRL level 3
Space Astronomy: astrometry by stellar interferometry	As SIM lite : Deep discovering and characterizing the presence of extraterrestrial planet by astrometry measurement using superconducting single photon detectors	 SSPD	Precision < 5 µarcsec 6m baseline Mag 10 star Exposure time : 225 seconds TRL level 2

Tab. 1. Overview SWIFTS's applications for space

IV. CONCLUSION

SWIFTS is a very competitive concept for space borne environment because it saves lot of weight and instrumental volume for valuable performances. Actual designs are not yet using the full capabilities of nanotechnologies permitting to imagine fully 3D spectrometric imagers. The success of the coming SWIFTS 400-1000 prototypes will certainly boost a next generation of small and cheaper instruments permitting to map both spatial and high spectral resolution.

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