A fully integrated Mach-Zehnder Microinterferometer on Lithium Niobate as an example of Micro Electro Optical System for Space Applications.

G.G. Bentini(1), M. Bianconi(1), A. Cerutti(1), S. Guerri(1), F. Tamarri(1), A. Zani(1)
P. Apollonio(2), P. Cerabolini(2), M. Chiarini(2), G. Pennestrì(2), W. Dinicolantonio(2)
I. Kostadinov(3)
V. De Cosmo(4), R.Guzzi(4)

(1)IMM-Section of Bologna - C.N.R.-Italian National Research Council, via Gobetti 101, 40129, Bologna (Italy)
(2)Carlo Gavazzi Space Spa, Via Gallarate 150, 20151 Milano (Italy)
(3)ISAC - C.N.R.-Italian National Research Council, via Gobetti 101, 40129, Bologna (Italy)
(4)ASI – Italian Space Agency, Viale Liegi 26,00198, Roma (Italy).

ABSTRACT

Micro Electro Optical Systems (MEOS) represent an attractive tool for the fabrication of small satellites and can play a key role in many space applications: in fact, they have rugged performances, reduced sizes and weights, low power consumptions and strong mechanical resistance. Further, by using batch processes, MEOS can be produced in mass, and, consequently, at low cost. All these items open the possibility to apply MEOS in redundancy, thus drastically reducing failure effects. In principle, a miniaturised system can be thought as the core of an ultra small satellite, which can be identified in the payload itself, equipped with few multifunction items, for attitude control, data collection and transmission. All these elements constitute the background for an easier access to space.

In this view, we have designed, produced and developed the first prototypes of an integrated scanning Fourier Transform Microinterferometer with Mach-Zehnder geometry. The miniaturised device is obtained by building up integrated optical waveguides on Lithium Niobate crystals (LN) and is electrically driven, without moving parts, by exploiting the electrooptical properties of the material. The input/output signals are injected and collected, respectively, by means of optical fibres, optically coupled ("pig-tailed") to the front-end channels of the integrated microdevice.

The microdevice operates the Fourier Transform of the input radiation and can be used for spectral analysis. In fact the input spectrum can be reconstructed starting from the output signal by means of Fast Fourier Transform (FFT) and de-convolution techniques. The microdevice weights few grams, its power consumption is of a few milliwatt and, in principle, can operate in the LN transmittance window (0.36μm -4.5μm). Preliminary tests were conducted in the Visible/NIR (0.4μm to 1.7μm), where spectral resolutions better than 0.5 nm were obtained.

A further step was the integration of the microdevice with a small telescope (12 cm long, with a 5 cm diameter) made in carbon fibre material. The telescope has a spherical mirror (10-cm of focal length, F/# = 2), which collects and injects the radiation in the microinterferometer input-fibre. The instrument furthermore integrates all the electronics, for signal driving and detection. The whole system weights less than 500 g and the telescope determines its dimensions. The whole power consumption is less than 3W. This allowed the realisation of the first prototype of a very light and compact system, suitable for spectral analysis in space applications.

INTRODUCTION

The application of small satellites to the development of space missions could represent an attractive tool for the reduction of operational times and costs. The types of missions, to which it is possible in principle to apply small and ultra small satellites, can span from scientific earth observation, to operational, public and commercial services, to technology demonstration. In practice the fabrication of reduced size satellite systems constitute the background for an easier access to space.

Within the process of size and consumption reduction, the Micro Electro Optical Systems (MEOS) can play a key role [1][2]: in fact, these miniaturised systems can provide a drastic reduction in dimensions without loosing rugged performances. Further, they can be produced in mass, by using batch processes of planar technology, thus giving rise to reduced costs. All these items show that MEOS can be applied in redundancy, thus drastically reducing failure effects.

The introduction of MEOS technologies in Space Applications implies the overcoming of important breakthroughs and the changing of solid paradigms. In Fact a miniaturised system can be thought as the core of an ultra small satellite, which can be identified in principle in the payload itself, equipped with few simple items, for driving, attitude control, data collection and exchange.

As a starting milestone, in the context of a Research Programme financed by ASI (The Italian Space Agency), we have designed, produced and developed the first prototypes of an integrated Mach-Zehnder Microinterferometer. The device demonstrated performances that make it suitable for Earth and Space observations; furthermore, due to its reduced size, weight, power consumption and cost, it can be envisaged as an ideal payload of ultra small satellites. In this philosophy three MEOS interferometers were integrated on a 12 cm long telescope, fabricated in carbon fibre, equipped with a spherical mirror (5cm in diameter and 10cm of focal length), together with the whole electronics, necessary for signal driving and collection. The small compact system can be thought as a first example of ultra-small payload, starting from which a very small satellite can be constructed.

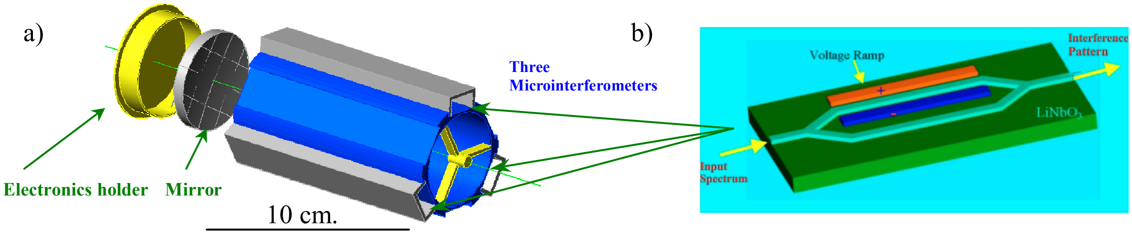

Fig. 1- a) design of the ultra-small satellite payload; b) schematic of the microinterferometer.

EXPERIMENTAL

Fig. 1 reports the payload for an ultra small satellite integrating three interferometers, a small telescope and the suitable driving/detecting electronics (Fig. 1a), and a detail schematic of a single microinterferometer (Fig. 1b).
As in any conventional interferometer, the radiation to be analysed is injected in the optical circuit and then split in two beams, each travelling through one of the two arms (Fig. 2). Before the output channel the two beams are recombined and give rise to an interference pattern (interferogram), depending on the path difference produced between the two arms.

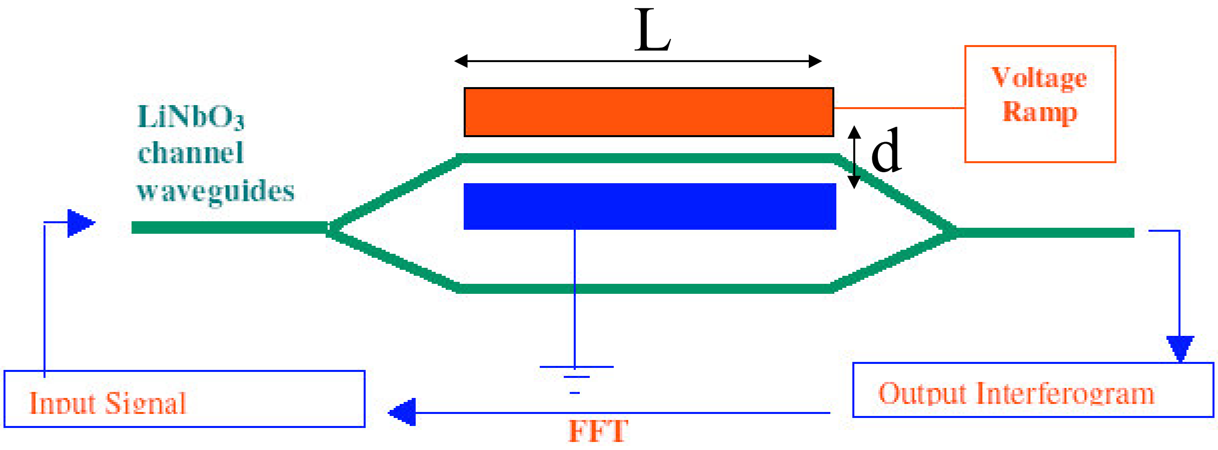

Fig. 2 - Schematics of the operation principles of a scanning Mach-Zehnder Microinterferometer.

This system works as a scanning interferometer, because the output intensity is monitored as a function of the optical path variation. The resulting output interferogram I_{out}^{tot} (Δp), where Δp is the path difference, represents in fact the Fourier Transform of the input spectral distribution as it can be deduced by the following relationship [3]:

$$I_{out}^{tot} = \int I(\kappa)[1+\cos(2\pi\Delta p*\kappa)]d\kappa\,, \qquad (1)$$

where $\kappa = 1/\lambda$ is the wavenumber of the incident radiation, κ_0 is the central wave number of the spectral distribution, the integration range is extended to infinity.
In our case every moving part is avoided by exploiting the linear electrooptical effect of LN. A voltage ramp is applied to one or both arms of the interferometer, so that to produce a proportional linear variation of the optical refractive

index, and a consequent optical path difference between the light beams travelling along different arms. In a balanced Mach-Zehnder configuration (same arm length) one can write:

$$\Delta p = L\ \Delta n\ , \tag{2}$$

where L is the arm length and Δn is given by:

$$\Delta n = r_{33} \cdot n_e^3 \cdot E / 2\ , \tag{3}$$

where r_{33} is the linear electro-optic coefficient along the optical c-axis, n_e is the LN extraordinary refractive index, and E is the electric field applied to the driving electrodes. A sensor is synchronised with the applied voltage ramp and collects, at each voltage step, the corresponding modulated output intensity (interferogram).

The instrument resolution can be expressed by [4]:

$$\Delta\lambda = 0.5 * \lambda^2 / \Delta p \tag{4}$$

and is dependent on the analysed spectral windows.

Optically polished LN wafers, X-cut oriented, were implanted with Carbon at 3.9 MeV, and Oxygen at 5.0 MeV respectively, with implantation fluences laying in the range $1 \div 6 \cdot 10^{18}$ ions/m^2 [5][6].

After the implantation process a further annealing procedure was applied in order both to recover the colour centres produced during implantation and to stabilise the damage profile. Structural and optical characterisations were performed in order to check the process results. The devices were then diced, front-end optically polished, fibre pig-tailed and finally tested in the visible/near infrared spectral region.

A one Hz voltage ramp with a maximum peak to peak amplitude of 80V was applied through the electrodes: the output interferogram was then collected by a silicon photo-diode and monitored by a standard oscilloscope.

The first tests were performed by coupling a He-Ne radiation source (λ =632.8 nm) as input signal. With a voltage ramp varying from -40 V to 40 V, the maximum refractive index variation Δn induced was close to 4×10^{-3} corresponding to an optical path difference close to 0.15 mm, as predicted by (2). Fig. 3a and 3b report the sampled interferogram and the corresponding FFT, respectively.

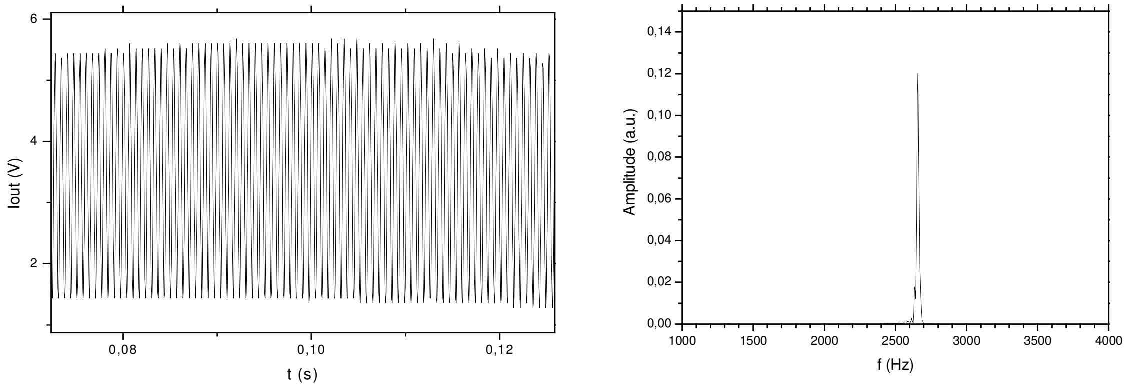

Fig. 3 - a) Interferogram as obtained from He-Ne laser source, b) corresponding FFT.

The interferogram of Fig. 3a presents a sinusoidal trend with a superimposed low period modulation. This effect is due to different factors. Firstly the laser line is not an ideal delta function, but has a finite width. Moreover there is the influence of the linear polarisation of the He-Ne laser incident light, in fact by applying an electric field to the arms, a rotation of the polarisation axis is produced. This gives rise to a periodic variation of the fringe contrast. These effects can be corrected by using suitable software de-convolution procedures and are negligible in the case of broad band radiation sources.

Radiation sources with low coherence length were experienced, by using both common Halogen Lamps and direct Solar Radiation. The whole wavelength range of analysis is limited at higher frequencies by the photo-diode sensitivity response (400-1100 nm in the case of a PIN Silicon Diode, 800-1700nm for an InGaAs photo-detector).

It is important to underline that the Mach-Zehnder interferometer has a working spectral window that is given in principle by LN transmittance, (0.36 μm to 4.5 μm). Thus, by adjusting the geometrical characteristics of the integrated optical circuits, it is possible to obtain prototypes suitable for analyses in different regions of the specified window.

As a first testing sample we collected through a little telescope direct solar radiation. The results we obtained are exposed in Fig. 4. Fig. 4a presents the interferogram and Fig. 4b, instead, reports its FFT (solid line) after the normalisation to the photo-detector responsivity function. A reference spectra is reported too (dotted line).

The spectrum we observed by pointing the sun directly in a July afternoon, shows very clearly the Fraunhofer lines. It was also possible to observe absorption lines due to O_3 near λ=500 nm. The possibility to observe the Fraunhofer lines, suggests that that the spectral resolution could be better than 1nm. In particular, the analysis of the spectrum reveals that peaks with Half Width at Half Maximum, (HWHM), narrower than 1 nm are recorded.

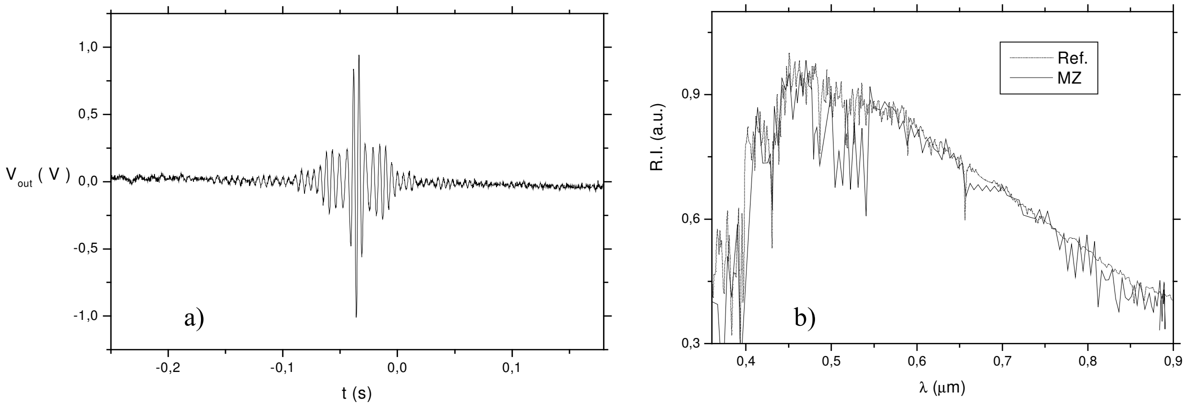

Fig. 4 - a) solar radiation interferogram, b) corresponding FFT(solid), reference (dot).

In a further experiment we performed absorption tests (Fig. 5) by introducing between the radiation source (250w Halogen lamp) and the light injection system an optically prepared cell for chromatography, containing an organic solvent (isopropyl alcohol). Little amounts of a common organic dye (Patent Blue) were successively added to the cell, in order to observe the absorption phenomena induced in the collected spectra. The same experiment was performed in two different spectral windows by using the same microinterferometer: this was obtained by only substituting the output Silicon PIN photo-detector with a InGaAs photo-diode, thus demonstrating the possibility to immediately extend the microinterferometer operation to the near IR region.

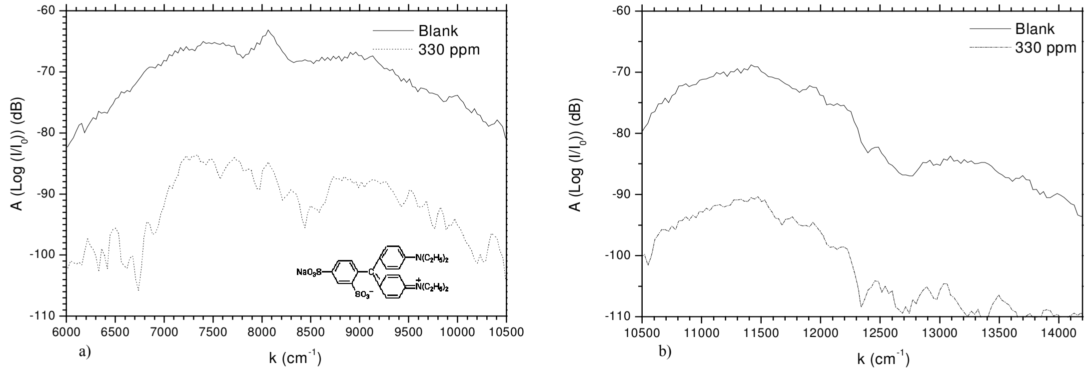

Fig. 5 - Absorption spectra of 330 p.p.m. of Patent Blue dye dissolved in isopropyl alcohol as obtained by using: a) InGaAs photo-diode as output detector, b) Si-PIN photo-diode as output detector.

A further step of miniaturization involved the radiation collection system and the electronic equipment for signal driving and handling. In order to fabricate a compact and portable system, three microinterferometers were installed as three independent spectral windows (spectral channels) on the body sides of a small telescope, realised in carbon fibre.

The telescope is equipped with a spherical mirror, focusing the collected radiation on a three-fibre bundle. Each fibre collects the focused radiation and conveys it in the input channel of a single microinterferometer. The telescope is also equipped with the electronics necessary both for the microinterferometers driving and for the handling of the output signals (detection, filtering and amplification)

Each microinterferometer is located in a separated box, fixed on a side of the telescope body. The same box also contains the corresponding photo-detector together with the preamplifier/amplifier electronic board, whereas the driving voltage ramp generator is located in a miniaturized board, placed in the lower part of the telescope body, below the spherical mirror. The main items composing the whole spectrometer are reported in Fig. 6. Fig. 6a represents a sketch of a section of the system assembly, showing one of the three interferometers fixed on the telescope body, the spherical mirror and the driving board.

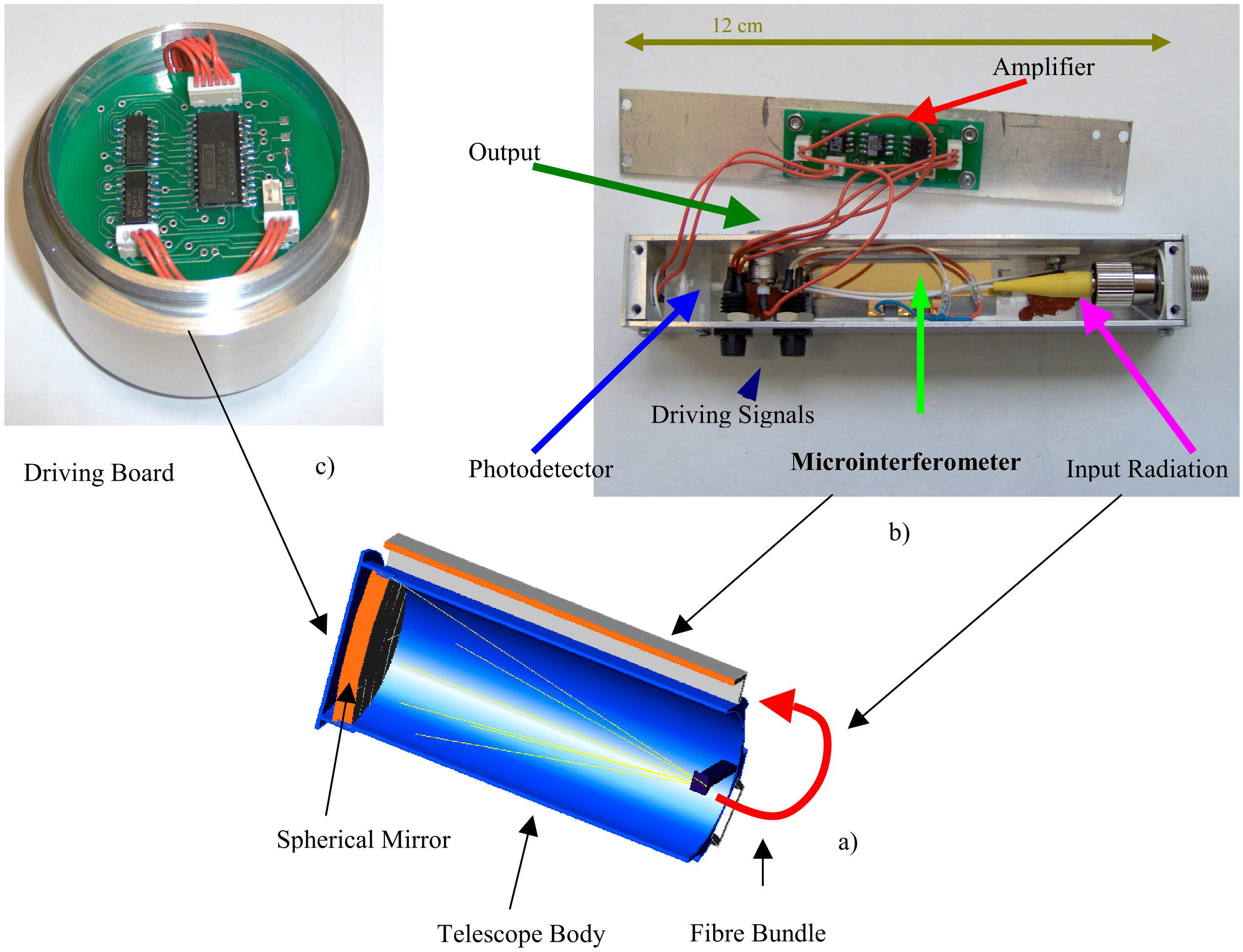

Fig. 6.- a) Telescope longitudinal section; b) Optical signal processing unit containing one microinterferometer, the photo-detector defining the spectral window, the output signal filtering and amplifying electronic board; c) Driving board for voltage ramp generation.

The telescope body is fabricated in carbon fibre, thus reducing both weights and thermal expansion. The whole length is 12 cm. and was established in order to fit the optical properties of the focusing mirror. The mirror is spherical, with a 5 cm diameter and is characterised by an F-number F/# = 2. At the focusing point a bundle holder is located within a precision positioning system, coaxial to the telescope axis, and fixed to the telescope body by three symmetrical branches (Fig. 7). The positioning system allows an accurate alignment and centring of the input fibre ends both along and around the telescope axis, in order to maximise the input light signal. Because of the reflective nature of the mirror, chromatic aberrations are avoided.

Fig. 6b shows a picture of one of the three boxes installed on the telescope body sides and containing one microinterferometer, its photo-detector and the filtering and amplifying board, which is placed on the cover lid. The fibre coming from the telescope focus is connectorised to the input fibre of the microinterferometer by using a standard fibre connector. Fig. 6c shows the driving board, which is located in a lower case, fixed at the telescope body below the spherical mirror, and drives the scanning in the three interferometric channels by generating a suitable voltage ramp.
Fig. 7 reports a picture of the complete system: its weight is around 500g, with power consumption lower than 3W.
The application of suitable photo-detectors allows the possibility to operate spectral analyses in three different spectral regions, within the limits imposed by the transparency range of both selected optical fibres and LN.
This first prototype demonstrates the possibility to produce very compact and rugged systems for space applications, obtained by applying MEOS technologies and is intended as a first demonstrator of a new generation of very small payloads starting from which ultra-small satellites can be realised.

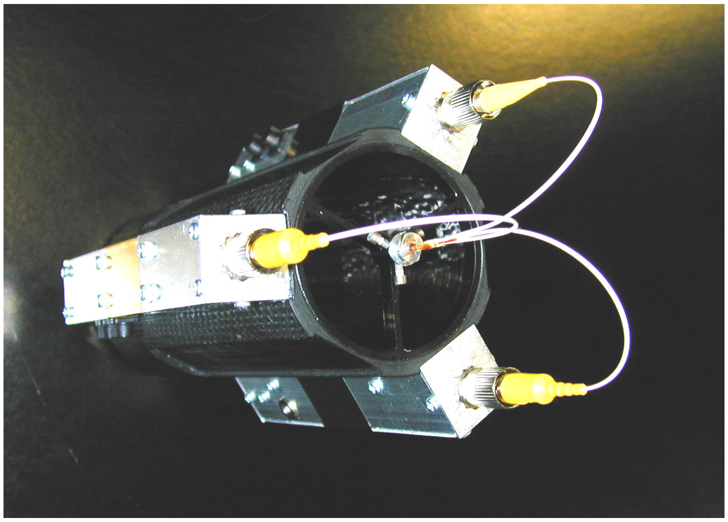

Fig. 7 - Fully assembled three spectral windows interferometric spectrometer.

CONCLUSIONS

The application of MEOS technologies allowed the realisation of an integrated scanning Mach-Zehnder microinterferometer on $LiNbO_3$. The performances of the microinterferometer were preliminary tested within the VIS/NIR region (0.4 μm -1.7 μm). The results of such tests are reported. By using the integrated microinterferometer as core device, it was possible to fabricate a very compact spectrometer. The whole instrument is composed of three microinterferometers (each one dedicated to a different spectral window), a small telescope for radiation collection and is equipped with the full miniaturised electronics, for signal driving and detection. Its weight is less than 500g, its power consumption is lower than 3W and can perform spectral analyses in principle on the whole transmittance region of LN (0.36 μm -4.5 μm). Due to the reduced size, weight and power consumption the miniaturised system can be thought as a first element of a new generation of very compact payloads, suitable for the realisation of ultra-small satellites by the application of MOES technologies as breakthrough solutions in space missions.

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