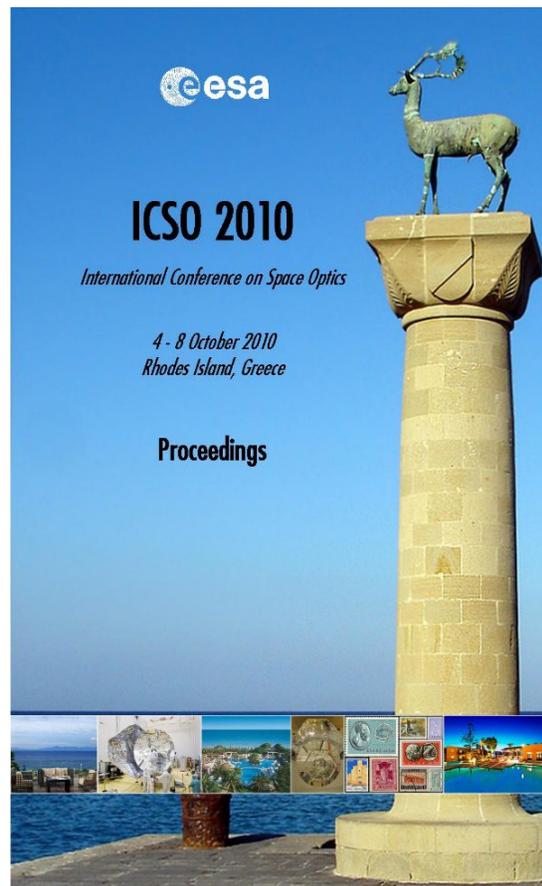


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APPLICATIONS OF FBG SENSORS ON TELECOM SATELLITES

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I. INTRODUCTION

Monitoring needs of spacecraft are rapidly increasing due to new and more challenging missions, along with demands to reduce launching costs by minimizing the manufacture, assembly, integration and test time and employing new low weight materials balanced by the need for maximizing system lifetime while maintaining good reliability. Conventional electronic sensors are characterized by their low multiplexing capability and their EMI/RF susceptibility and it is in this scenario that Fiber Optic Sensors (FOS) in general, and more specifically Fiber Bragg Grating (FBG) technology offers important benefits, improving in various ways the already deployed sensing subsystems (e.g. reducing the weight associated with sensor cabling, increasing the number of sensing points) and enabling new monitoring applications that were not possible by using conventional sensing technologies.

This work presents the activities performed and the lessons learnt in the frame of ESA's ARTES-5 project "Fiber Optic Sensing Subsystem for Spacecraft Health Monitoring in Telecommunication Satellites". This project finished in July 2009, with the implementation and testing of two different demonstrators employing FBG sensor technology: FBG sensors for temperature monitoring in high voltage environments, and in particular in several parts of electric propulsion subsystems [1], and FBG sensors for thermal monitoring of array-antennas during RF testing [2].

In addition, the contacts performed with different actors within the space community allowed the identification of a special area of interest for the substitution of regular thermocouple instrumentation by FBG technology for thermal vacuum ground testing of satellites.

II. IDENTIFIED APPLICATION DESCRIPTION

Thermal Control in Satellite Structural Panels

Temperature monitoring is massively performed on satellite's communication module (CM) lateral walls on which the payload equipment is attached. Also temperature measurements are taken at the CM upper and lower floors and at the service module (SM) walls and floor. As an example, in the Geosynchronous Telecommunication Satellite EUROSTAR3000 (EADS ASTRIUM's satellite) more than 180 thermistors are reported for thermal mapping of the CM and SM floor and walls, where thermistors are located either directly bonded to the structure or at specific sensitive equipment foot. Harnessing for these temperature sensors is heavy and mainly its installation is very time consuming.

By employing FBG sensor multiplexing capability, reduced harness MAIT time and weight can be obtained. Two different approaches can be followed for this kind application: sensor embedment into the panels or sensor bonding on panel surface.

The first approach impacts panel manufacturing and raises issues on qualification process of these new panels. It also limits the technique to measuring spots that are placed on the panels themselves and not on top or inside equipment boxes. As an advantage of the embedding approach, the thermal harness would be integrated into the panel once manufactured, and there would be no further need for thermal harness installation at a later stage.

The second approach is to directly replace the usual thermistors by surface bonded FBG temperature sensors, taking benefit from the multiplexing capabilities of the technology to reduce cabling and MAIT time. This approach would thus have no impact on panel manufacturing, and it would limit changes to the thermal harness design and installation processes. This approach is also applicable to both sensors placed on panel surfaces and on top/inside equipment boxes. It is this second approach that has been followed on the present project.

Analysis of the application for temperature measurements required over a telecom satellite EUROSTAR3000 yields a 74% mass decrease using FBG sensors for direct replacement of thermistors (surface mounting). Still, given the low overall mass of the electrical harness (lower than 2kg), weight reduction does not seem to be a driving force towards the adoption of FOS technology. It is the cable length reduction (from over 350m to less than 100m) which can in fact have a greater impact, reducing AIT time and effort.

Sensor splicing is required in order to avoid excessive use of optical connectors, which are the greatest contributors to overall weight of optical solution. Optical connectors are to be employed only at critical

locations of the panels, such as panel joints in which several assembly and disassembly operations may be required. For the splicing process during installation, handheld optical splicing equipment is currently commercially available.

Additional interest has been shown during the execution of this work for FBG employment on thermal ground testing, which involves a much greater amount of temperature measurements (around 400 thermocouples employed for testing and afterwards removed for flight). The incorporation of FBG technology on these tests would provide a greater reduction of AIT effort with the higher number of sensors, it would provide improved signal quality and would also allow for only partial disassembly of the test harness required since some of the test sensors would be the ones left for flight.

Temperature Monitoring During Array Antenna RF Testing

One of the challenges encountered during antenna power RF testing, and specifically in array type antennas, is to determine the temperature of certain elements of the antennas, either internal or external, while subjected to RF path. Temperature tests over antenna parts are normally requested in order to provide early detection of design problems which often translate into non uniform temperature distributions.

On such applications the effect on the RF behaviour produced by the metallic cables of thermocouples and/or thermistors at certain frequencies is a limiting factor when using standard sensors. In some cases, temperature measurements had to be estimated even using qualitative temperature indicators, such as paper films on which colour changes as a function of the maximum attained temperature. Such a sensor provides a reference of the temperature achieved, but clearly lacks the accuracy of a conventional sensor.

The availability of FOS temperature sensors immune to RF and with a thickness that is compatible with the interlayer gaps on this type of antennas makes them an ideal solution to perform accurate thermal testing. FBG sensors thus provide a solution for inner layer temperature monitoring during RF testing without distortion of antenna operation. This also implies that sensors could also be left embedded for flight.

Aside from the RF immunity, a key issue for this application is the sensor installation flexibility. Since the number of measurement points for this application is typically small (<10), terminal FBG sensors with individual fibers are presented as the optimum choice to maximize flexibility on the installation process. Sensors must also be compatible with antenna inter-layer separation, which is a few millimetres. Sensor design and fiber coating and protection must be a trade-off between ease of installation and impact on antenna performance due to size.

Temperature Monitoring In Electric Propulsion Subsystems

A key difficulty for monitoring the different parts of an electric propulsion subsystem is the presence of a vacuum environment where a combination of high EM fields and free charged particles limits the possibilities of using conventional electrical sensors.

Within an ion engine propulsion subsystem, three main parts have been identified as having relevant monitoring requirements:

- Temperature monitoring inside the ion engine thrusters: The impacts of the accelerated ions on the thruster walls are expected to be one of the main causes of degradation and lifetime limitation for ion engines. In these systems, temperature monitoring on the thruster would provide some information on the degradation of the ion engine.
- Temperature monitoring in the High Voltage Power Supplies (HVPS): specific components on the HVPS such as the high voltage transformers and the power transistors are specially indicated for temperature monitoring due to their greater heating during high voltage power supply operation.
- Temperature monitoring along the high voltage cable from HVPS to the engine: Given the high temperatures attained on the ion engine, custom made high-voltage cables are required from the high voltage power supplies inside the SC to the ion engine thruster. Temperature measurements are required along this cable to provide thermal mapping and check on the cable behavior.

For this application, FBG sensors provide improved signal integrity due to immunity to the EMI environment, and could be an enabling monitoring technology.

II. FBG SENSOR DESIGNS

For all the identified applications, minimum size and weight sensor designs are critical, and thus the proposed designs must ensure strain cross-sensitivity elimination in a miniature package. In addition, metal free designs have been employed to fulfil the requirements of the HV and RF applications.

Two types of FBG sensors have been designed and tested on the different demonstrators: serial sensors are employed to provide high multiplexing capacity and terminal sensors are used to optimize installation flexibility.

The serial sensor provides access to both fiber ends, thus allowing for daisy-chain of several sensors and fully exploiting the multiplexing capabilities of the FBG technology. The design avoids strain cross-sensitivity due to the S-shape design, which leaves the sensitive element (~8mm FBG) on the fiber neutral axes. Heat transfer is achieved through the epoxy and low mass silica part into the optical fiber

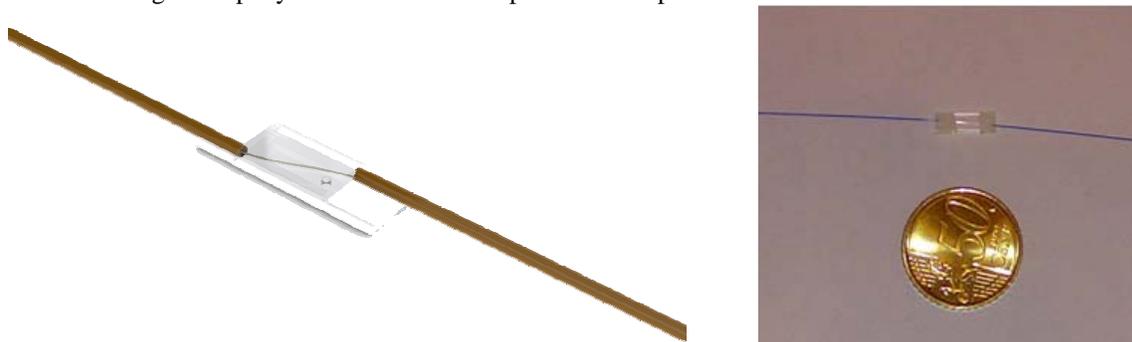


Fig. 1. Serial temperature sensor design and picture.

The terminal sensor provides access to just one fiber end, thus maximizing installation flexibility in difficult to reach measurement points, such as on top of electronic equipment boxes. The design avoids strain cross-sensitivity due to terminal nature of the packaging (sensing element only fixed from one end). Again, the heat transfer is obtained through the epoxy and low mass silica cup to the optical fiber.

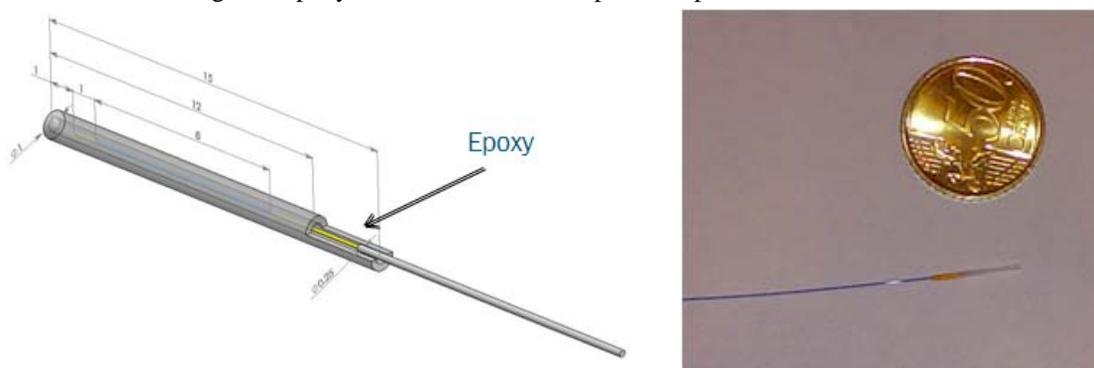


Fig. 2. Terminal temperature sensor design and picture.

The main characteristics of the designs are summarized on table 1.

	Serial design	Terminal design
Size	10 x 3.9 x 1.2mm	15mm x Ø1mm
Weight	0.06gr	0.08gr
Type of fiber	Standard SMF fiber with Ø150µm polyimide coating	Standard SMF fiber with Ø150µm polyimide coating
Materials	Hollow capillary made on clear fused quartz.	Protection cap made on clear fused quartz.

Table 1. Main characteristics of FBG miniature temperature sensor designs

Simple samples have been provided for both sensor design, and results on temperature cycling can be seen on Figure 3 for samples bonded to an aluminum substrate using different fixation mechanisms (epoxy and Kapton tape).

Fair strain cross-sensitivity elimination has been achieved by both designs, since temperature sensitivity of the sensors is similar to a loose FBG, thus showing removal of the strain effect of the aluminum substrate expansion. Would the strain effect have not been removed, the thermal expansion coefficient of the aluminum would have yielded a sensitivity of 35.7pm/°C. Still, a slight non linear behaviour of the serial sensor differs from the usual non-linear response of the thermo-optic coefficient of silica, which suggests some residual strain effect on the sensor response for this design.

Additional results for vacuum operation, high temperature (400°C were attained), high voltage (1800V), plasma, RF environment and high temperature gradients (70°C/mm) will be presented on the following sections.

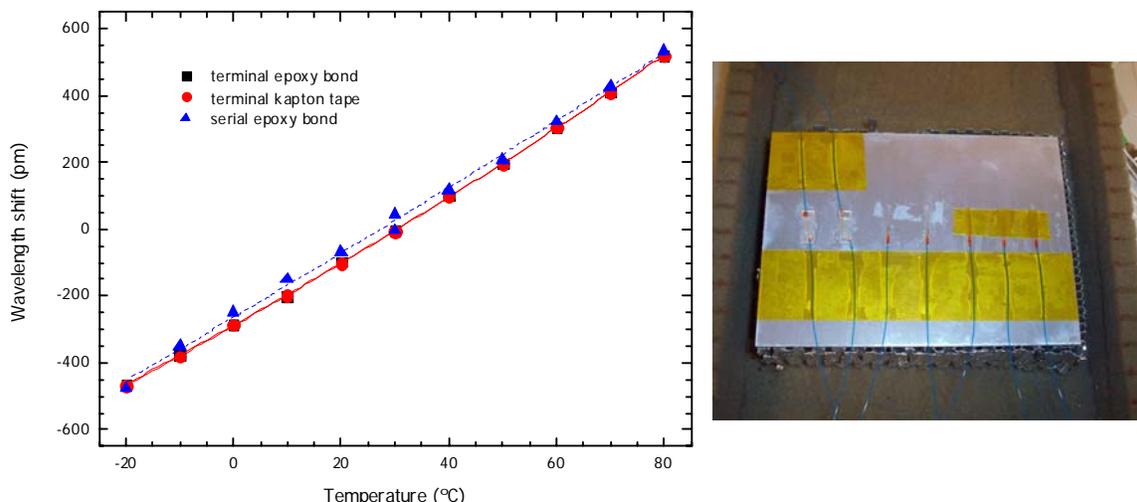


Fig. 3. Simple sample response test results and picture

III.- DEMONSTRATOR DESIGNS AND TESTING

Temperature monitoring in electric propulsion subsystems

The demonstrator implemented and tested incorporates FBG sensors for the three parts already identified: Temperature monitoring inside the ion engine thrusters, Temperature monitoring in the High Voltage Power Supplies (HVPS) and Temperature monitoring along the high voltage cable from HVPS to the engine

On the demonstrator, FBG temperature sensors have been located on different spots resembling the thruster's walls, the solenoids and a high temperature spot. Different FBG sensor packaging designs have been tested: for the medium temperature range (<120°C) miniature S-shape serial sensors have been used to remove strain effects while providing high multiplexing capability and terminal sensor designs have been used for the high temperature spots (<400°C). The maximum temperature that can be handled by these sensors is limited by the optical fiber coating material (polyimide/Kapton), which is 400°C. Overall, 5 FBG sensors have been placed on the nozzle: 2 serial sensors on the high voltage resistors, 1 serial sensor on the coil and 2 terminal sensors on the hot spot. For the HV cable, the approach on the demonstrator has been based on integrating a polyimide flexible tube along the cable, having a fiber containing the bare FBG sensors loose inside the outer tube. Three sensors have been integrated on the loose tube, 30cm apart. On the demonstrator HVPS 10 serial S-shape FBG sensors have been placed on different spots of the high voltage power supply and induction heating cards. One additional terminal sensor has been placed inside the potting employed for high voltage component isolation.

All the 19 sensors on the demonstrator are simultaneously measured by a single interrogation unit. Also redundancy to fiber cuts has been proven by using an electro-optic switch.

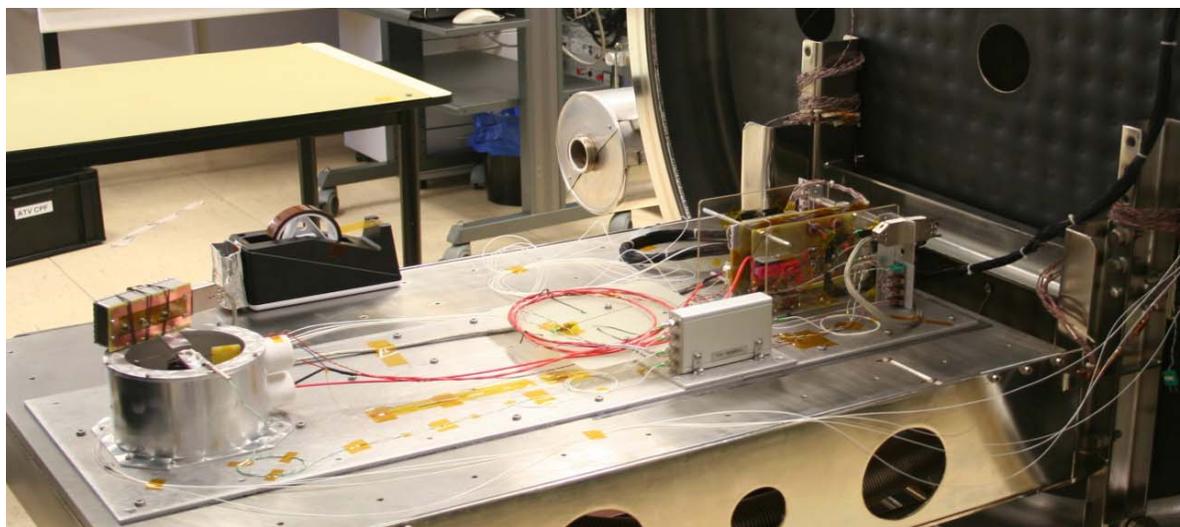


Fig. 4.- Mock up testing at Astrium-CRISA's vacuum chamber (from right to left on the picture: HV electronic card, HV cable and nozzle mock-up). Proc. of SPIE Vol. 10565 1056517-5

Testing has been performed both at ambient pressure and on thermal vacuum. High voltage, high magnetic field, plasma and temperature gradient conditions have been tested, providing comparative measurements between FBG sensors and thermocouples.

As an example Figure 4 provides results for the FBG sensors placed on the hot spots of the nozzle (temperatures over 300°C) during a vacuum test. The hot spot is a small area (Ø 15mm) metallic part which is being induction heated by the application of a high magnetic field. The physical configuration of the demonstrator also generates large temperature gradients on this area, which have been estimated to be as high as 70°C/mm.

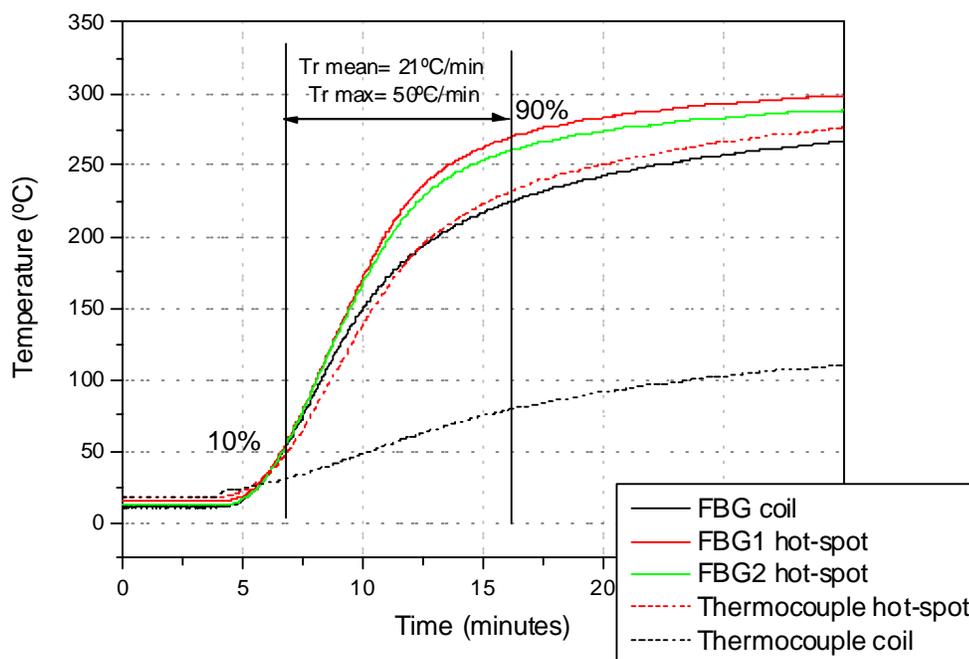


Fig. 4.- Thermal vacuum high-temp measurements using FBGs and thermocouples

As shown in the previous figure, in the presence of high temperature gradient fields, the FBG sensors are better able to measure the local temperature than conventional thermocouples. This is explained by the fact that the thermal impedance of the fibre optic cable is much greater than the thermal impedance of the metallic wires constituting the thermocouple, and thus reduce the temperature leakage through the cabling. Response time of the FBG sensor designs is also slightly better than that of the thermocouples.

FBG sensors located in the HVPS and on the cable, where small temperature gradients are present provide good tracking with the thermocouples. In high voltage conditions, the FBG measurements are not altered due to presence of EMI, whereas the thermocouple measurement unit is affected from electrical transients, and, in a lesser form, from AC magnetic fields. In plasma, we are able to measure temperature transients using the FBG measurement system.

Antenna Demonstrator Description

Demonstration of the application of FBG technology for array antenna temperature testing has been performed on two different antenna samples: a stripline Wilkinson divider breadboard used for the centre divider of the NAVANT (transmit antenna for GALILEO system) and a 1:3 Divider used in a NASA's Mars ROVER antenna. Different fixation mechanisms have been tested to place the sensors on different antenna parts, specifically on top of the inner copper tracks and resistors, and on the antenna external surface. Comparative analysis of the performance of FBG sensors attached by Kapton tape, Flashbreaker tape, EC2216 epoxy adhesive and by pressure on the Rohacell layers themselves has been performed. Also additional thermocouples have been placed on the antenna surface to provide comparison between FBG temperature measurements and conventional instrumentation (thermocouples).

S parameter measurements have been taken before and after FOS installation in order to assess the impact of the inclusion of the sensors in the antenna RF performance. Very small variations have been observed for the transmission, reflection and loss parameters on both samples, which are most likely due to sample re-working during sensor installation rather than to the presence of the sensors themselves. This indication is further supported by the fact that some of the RF parameters were even improved after sensor installation.

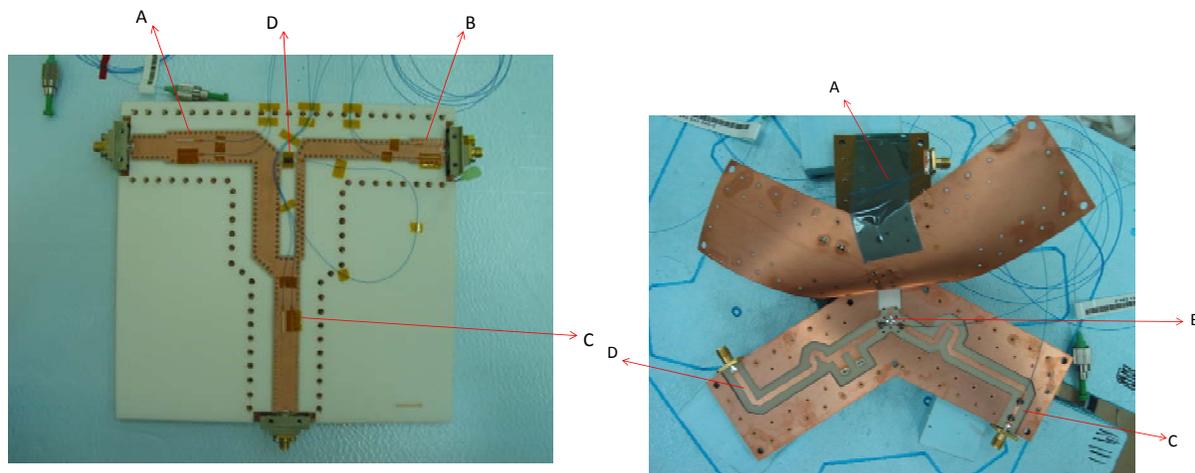


Fig. 5.- Left: 17 FBG sensors placed on inner layers and surface on a Wilkinson divider from GALILEO's NAVANT antenna. Right: 9 FBG sensors placed on inner layers and surface on a Mars ROVER divider sample

During antenna power testing a comparative analysis between FBGs and thermocouples and the effect of different fixation mechanisms on the temperature measurements have been assessed. Very good agreement has been obtained between FBG and thermocouples, and the effect of the different fixation mechanisms (kapton tape, epoxy adhesive EC221 and just mechanical pressure of the antenna layers) showed no relevant difference.

IV. CONCLUSIONS

Within this project three main applications have been identified for the incorporation of FBG sensors in telecommunication satellites, all of them involving temperature measurements: thermal control in satellite structural panels, temperature monitoring during array antenna RF testing and temperature monitoring in electric propulsion subsystems. From these applications, the first one mainly takes advantage of the multiplexing capability and reduced cabling effort provided by the technology, while the other two exploit the electrically passive nature of the optical fiber. One important aspect to underline is that, while on the first application FOS technology would be a substitute of the currently available solutions, the last two cannot be fulfilled by regular instrumentation and thus the proposed approaches would provide an enabling solution to current monitoring need.

Two different temperature sensor designs have been designed, implemented and tested, providing at the same time minimum size and removed strain cross-sensitivity. The terminal design optimizes sensor installation flexibility and is suitable for high temperature measurements, while the serial design optimizes sensor multiplexing capabilities. The combination of both sensor designs on the same network has also been demonstrated to optimize overall solution performance.

Sensor performance on vacuum, high voltage, high magnetic field, plasma, high temperature (400°C), high RF field and high temperature gradients has been tested, providing results which are equal or better (e.g. in high temperature gradient applications) to those obtained with thermocouples.

Still further development is required before final application into commercial telecom satellites. The development roadmap towards application of the technology in telecom satellites should focus on two main issues. The first one is the mechanical design of the sensors, providing further testing campaigns to assess compliance with the requirements with respect to vibration and shock. Also additional testing campaigns would be required to evaluate the long term performance of these sensors under the environmental conditions present in a telecom satellite. The second development field is the Interrogation unit development. The interrogation unit equipment must be redesigned to be compliant with the requirements (environmental, functional and economical) of a telecom satellite application. The new design should also ensure compatibility with existing temperature measurement units already used in telecom satellites.

IV. REFERENCES

1. F. Pedersen, S. Abad, F. M. Araújo, L. A. Ferreira N. Karafolas. "Temperature Monitoring in Space Propulsion Systems" 2010 Space Propulsion conference, 3rd to 6th May 2010. San Sebastian, Spain.
2. Abad S., Araújo F.M., Ferreira L.A., Pedersen F., Llorente de la Fuente J.J., McKenzie I. & Karafolas N, 'Fiber Bragg Grating Sensor Applications for Thermal Monitoring in Satellites', International Conference on Space Optics 2008, October 13 - 17, 2008 Toulouse, France.