TESTING OF OPTOELECTRONIC COMPONENTS FOR INTEGRATION INTO SPACE-ORIENTED FIBER BRAGG GRATING MONITORING SYSTEMS

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INTRODUCTION

Spacecraft structural health-monitoring applications are pushed forward by increased constraints in the cost of launching payloads into orbit that dictates major reduction in structural weight only attained through the use of advanced materials and innovative manufacturing methods. On the other hand, the reduction in structural weight must be tempered against the increased demands on performance, damage tolerance, and lifetime durability [1-3].

The present paper introduces a demonstrator that shall perform temperature measurements by means of Fiber Bragg Grating (FBG) optic sensors. The aim of the work being undertaken is, on one side, to demonstrate the advantages of using this technology with respect to present temperature monitoring techniques in both telecom satellite and launcher applications, and on the other side to reach the TRL-5 Technology Maturity for Crisa and FiberSensing. Towards this goal, several optoelectronic components are being tested following space requirements in order to be integrated as part of the FBG systems under development. These pre-validation tests are being carried out in collaboration with ALTER Technologies, and are meant to de-risk the full system development plan from the early design stages. This paper presents a description of the system focused on the use of optical components.

FIBER OPTIC SENSING

The Fiber Optic Sensing (FOS) system under development is a measurement system composed by FBG sensors, optical harness and an interrogation unit, whose interfaces are compatible with the existing thermal monitoring system so it can be used as a replacement for the latter. FOS technology can be used for measuring other analog parameters (strain, displacement, acceleration, inclination, pressure) using the same interrogation unit, by adding different types of FBG sensors.

A fiber Bragg grating is a small size microstructure (less than 10 mm long) that can be photo-imprinted in photosensitive optical fibers by side-exposure to patterned UV laser radiation.

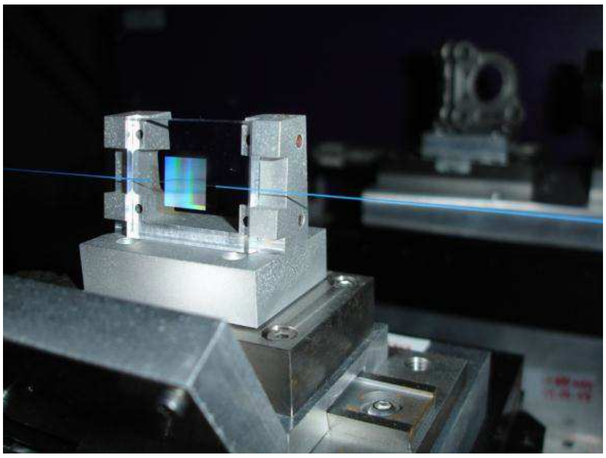

Fig. 1: FBG Manufacturing setup at FiberSensing

Such a microstructure consists on a periodic modulation of the refractive index of the core of the optical fiber that is characterized by a narrowband resonance spectral reflection. Since this is a deeply embedded device in the optical fiber structure, the resonance behavior strictly follows external actions in the exact proportion as the silica matrix surrounding the component. This results in a localized sensor offering high sensitivity to temperature (mainly due to the thermooptic coefficient of the optical fiber) and strain (mainly due to the physical variation of the period of the pattern due to the deformation), which both translate into a shift of the reflected wavelength.

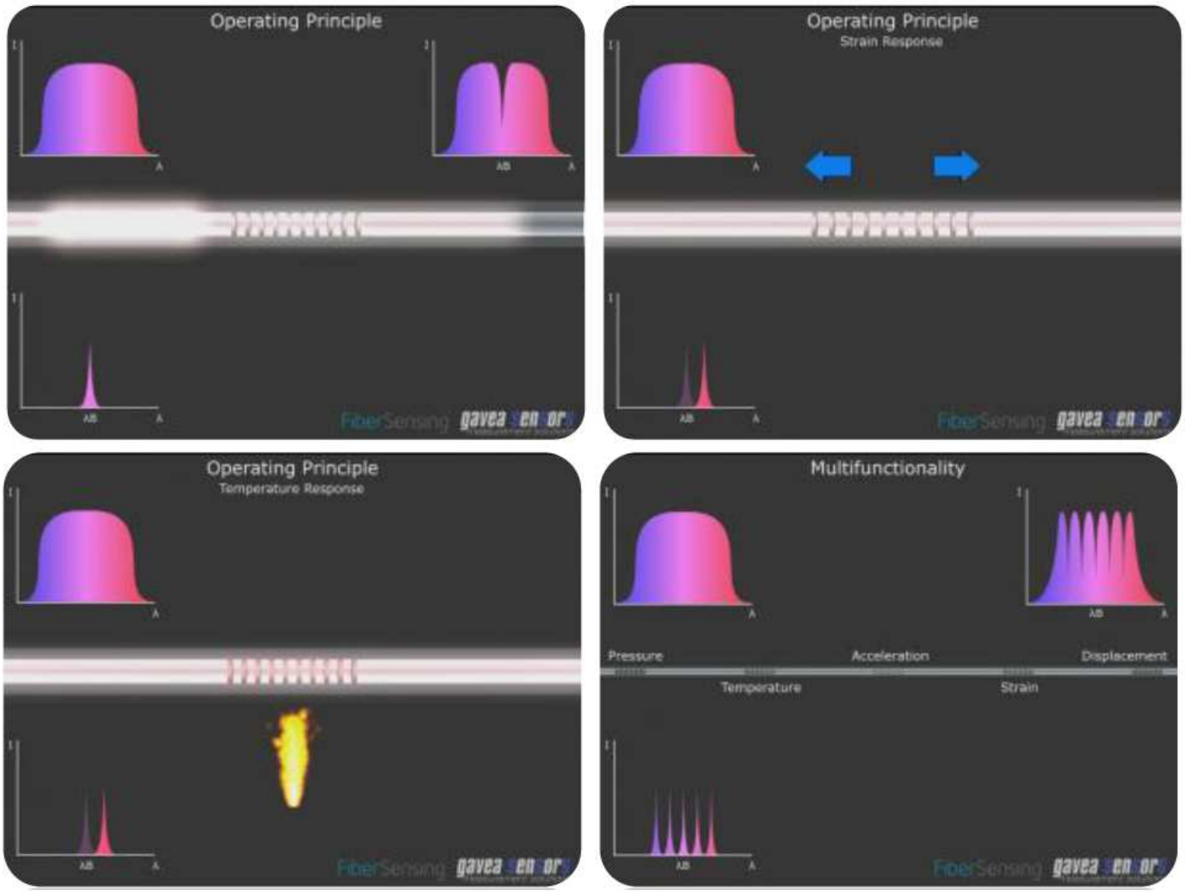

Fig. 2: FBG Operation principle. The fiber Bragg Grating acts as a wavelength selective mirror. This means that when light from a broadband source is injected in the optical fiber, only light within a very narrow spectral width, centered at the Bragg wavelength, is back-reflected by the grating. The remaining light continues its way through the optical fiber without experiencing any loss. The variation of the temperature or of the strain affects this reflection. Monitoring it allows the calculation of the actual temperature or strain.

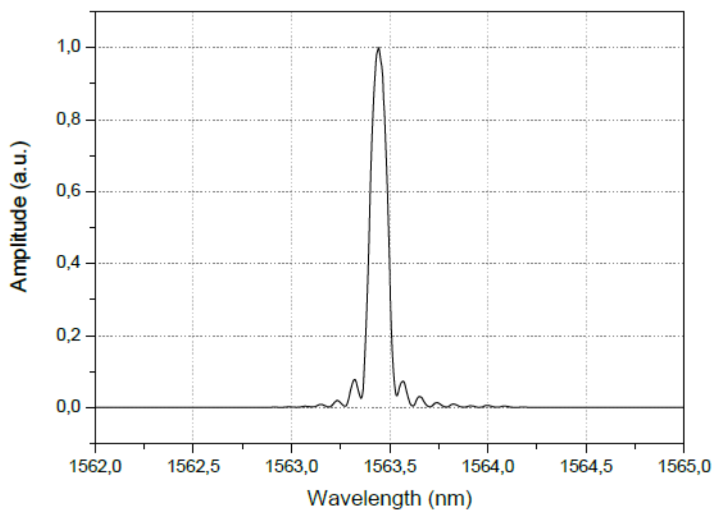

Fig. 3: Typical FBG reflection response

FBG sensors are thus inherently sensitive to temperature and strain, showing sensitivities around 10pm/ºC and 1,2nm/mε at 1550nm operation band. Also acceleration, vibration, displacement, pressure and inclination sensors [4] can be attained by providing packaging designs that translate all those physical parameters into strain on the FBG element, although these designs are usually larger in size than their conventional electronic or MEMS-based counterparts. Even humidity [5], large electric field [6] and chemical sensors [7, 8] have been demonstrated at research level.
As already stated, all measurements translate into a reflected wavelength shift, which is the parameter to be detected at the data acquisition equipment (interrogation unit IU). All sensors can eventually be addressed using the same IU equipment, and the only difference among the different types of sensors would be the calibration formulas applied for wavelength to measurement conversion. There are several approaches towards the implementation of interrogation units for FBG sensors, from which the tunable laser approach has been selected for the current development since it maximizes multiplexing capability and sensor count, and provides greatest long term accuracy of spectral measurements.

Although standard FBG sensors are commonly designed to operate in a temperature range from -20 to 100ºC, usually limited by the optical fiber coating materials, their operation can be easily extended to match an extended -196ºC to 160ºC range by properly selecting the fiber coating materials to be either high temperature acrylate or polyimide. Anyhow, polyimide coated fibers are required for space applications due to outgassing of acrylate.

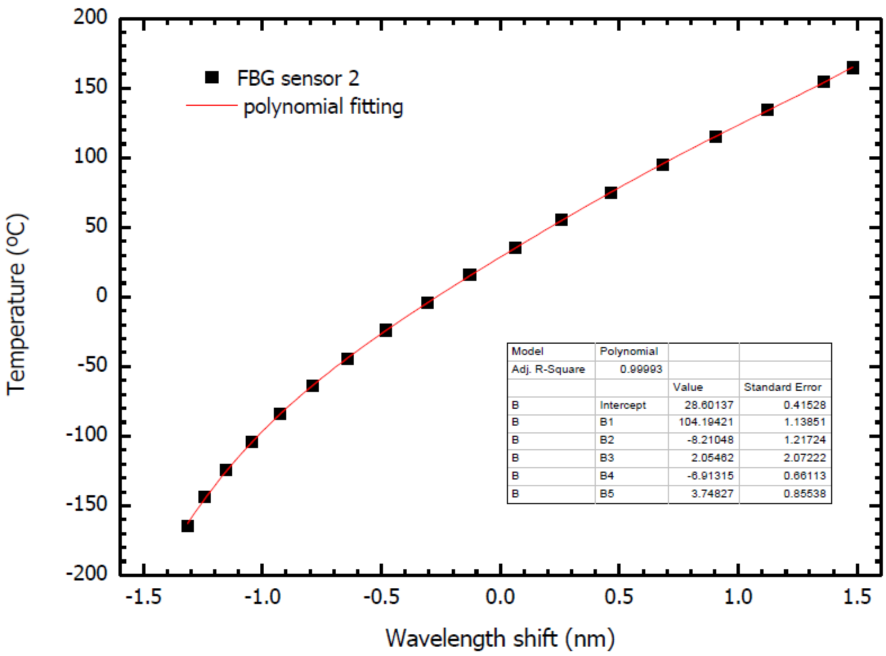

Fig. 4: Extended temperature operation (-160 to 160ºC)
for a FiberSensing's temperature sensor design

The present project has been focused on FBG based temperature sensors on the -55 to +125ºC range to achieve temperature mapping of telecom satellites as described above.
In addition to good performance in terms of reliability, measurement accuracy and range the sensor design must fulfill:

- Minimized size and weight
- Ease of handling during installation
- Two side ended to allow multiplexing
- Good strain decoupling

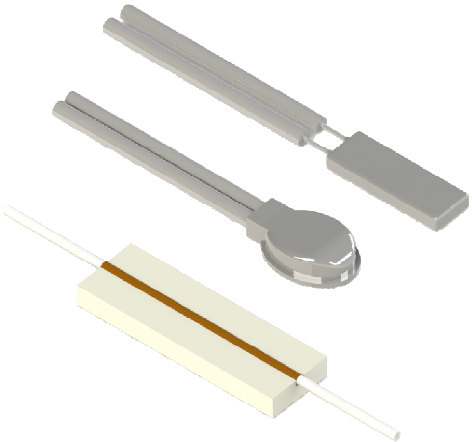

Fig. 5: FBG temperature sensor compared to conventional electrical counterparts.

FOS INTERROGATION UNIT

Additionally to the FBG sensors, a complete FOS needs an interrogation unit for addressing the Fiber Bragg Sensors.

The system is therefore composed by an Interrogation Unit (IU) plus an Optical Harness (OH) in which FBG sensors are embedded. The Interrogation Unit is capable of reading several sensor arrays simultaneously, also providing redundancy to single-point fiber cuts.

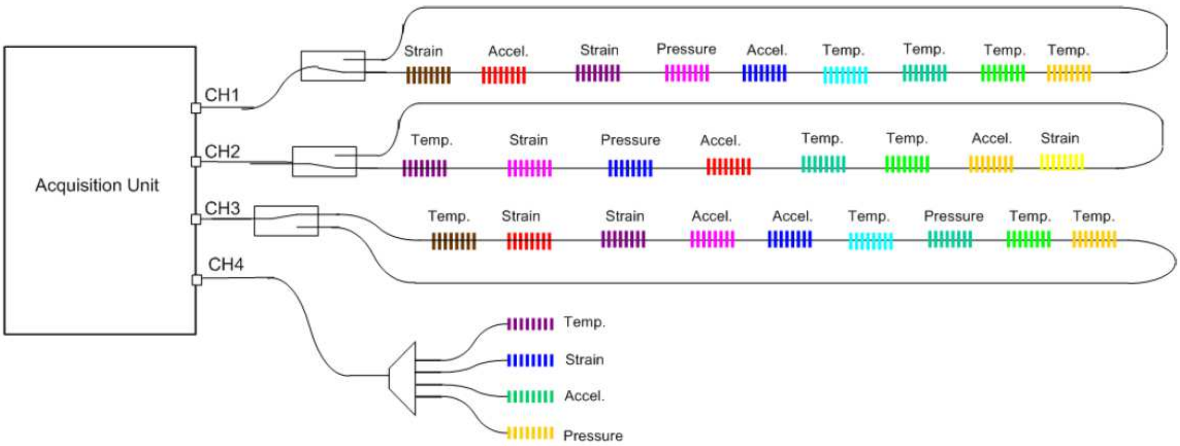

Fig. 6: Example of a multifunctional FBG based sensing network

On the present demonstrator, the interrogation unit includes a group of function called FOS CONTROL and another called FOS OPTICAL, which correspond to separate Printed Circuit Boards (PCBs) of the FOS demonstrator. These elements are discussed in detail in the next paragraphs.

FOS_CONTROL: This assembly includes basically the electronic functions of the unit, except those that due to the very restrictive constraints and the intimate relationship with the optical elements of the system need to be in close proximity to them.

FOS_OPTICAL: This assembly includes all the optical components, plus those electronic functions that are required to stay in close proximity to the optical elements affected by them. The included functions are:

- Tunable Laser, a fiber laser composed by several elements connected by optical fiber:
    - SOA (Semiconductor Optical Amplifier): Generates the optical wideband signal

  - Isolators: Allow the light to travel through the fiber in one direction only
  - Tunable Filter (TF): a very narrow filter controlled by a continuous analog signal that allows the laser perform a wavelength sweep over time
  - Coupler: divides the light power into 2 branches, with different coupling ratios.
- Optical Distribution
  - Couplers (see above)
  - Optical Switches (SW) or VOAs (Variable Optical Amplifiers), to block the light on one of the fiber ends when the fiber is intact
- FP: Fabry-Perot Etalon, used to provide a grid of wavelength reference peaks equally spaced in the operation range
- Optical Add-Drop Multiplexer (OADM): Used to break the symmetry of the FP
- Photodiode detectors (PD)
- PD_AMP: Transimpedance Amplifiers (TIAs). Amplify the small signal detected by the photodiodes to levels that can be handled by the filters and the ADC in the electronic section of the module.
- RAMP_DRV: Electronic function to provide a very accurate, very low noise analog voltage ramp to the tunable filter in order to do a sweep of the full wavelength range of operation over time
- OPT_CONN: Optical connectors for the OH.

MECHANICAL DESIGN

The complete Interrogation Unit has been design to be a module of RTU2015, currently under development at CRISA. FOS shall be a plugin module taking up 2 physical slots of the RTU, due to the volume needs of the optical components and the fiber routing.
However, the FOS module will be a single module with respect to the electrical interfaces and the connections to the Mother Board.
The focus of the architecture for the demonstrator in the present project, however, is not on the internal interfaces of the RTU2015 (TM/TC and power), which are considered standard technology, but on the parts of the FOS system that deal with new photonics technologies. However the mechanical design considering this as a RTU2015 module has some impact on the mechanical tests. Therefore the vibration and shock tests were performed with the samples mounted as in the final application.

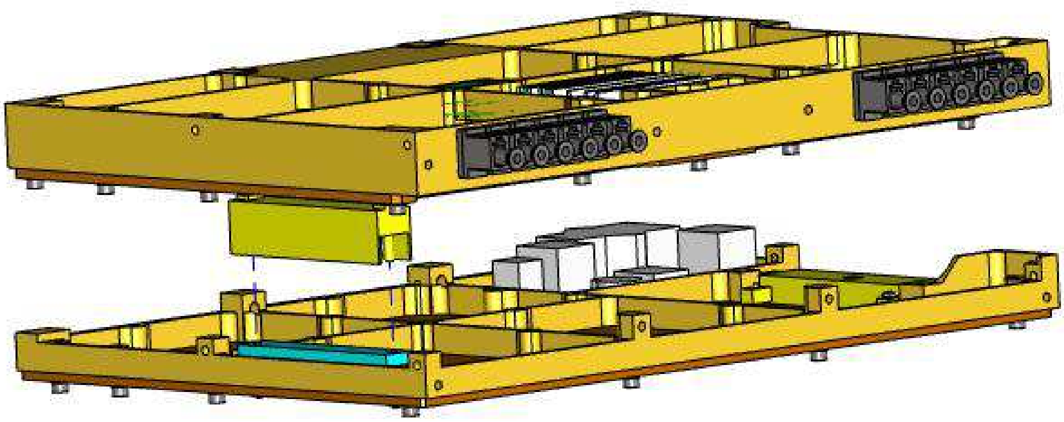

Fig. 7: Complete FOS module (both boards will be closed together, but they are shown separated for clarity

CRITICAL PARAMETERS OF OPTICAL COMPONENTS

The following table presents the critical parameters of the optical components to be fulfilled within the entire temperature range. These parameters are considered critical from the point of view of the final application (i.e. for being used in the implementation of the FOS interrogation unit):

Fiber Optic Component	Critical Parameter 1	Limits	Critical Parameter 2	Limits	Critical Parameter 3	Limits
SOA	gain decrease	<2dB	drive current increase	<50mA	TEC current increase	<250mA
tunable filter	free spectral range	>110nm	side-mode supression	>20dB	insertion loss increase	<1dB
DWDM/OADM	spectral shift	±100pm	insertion loss increase	<1dB		
wavelength locker	spectral shift	±5pm	responsivity reduction	<0.1A/W		
isolator	overall isolation	>20dB	insertion loss increase	<1dB		
couplers	insertion loss increase	<0.5dB	coupling ratio variation	<1dB		
photodetector	responsivity reduction	<0.1A/W	dark current	< 10nA		
connectors	insertion loss increase	<0.5dB				
VOAs/optical switches	attainable attenuation	>25dB	insertion loss increase	<0.5dB		

OPTOELECTRONIC COMPONENTS PRE-VALIDATION

The optical components are considered the most critical ones in terms of space environment suitability [9]. For this reason a preliminary selection of components has been done including a pre-validation of those considered as the most critical among them.

An analysis of the heritage and previous experiences lead to the necessity of pre-validation of the following components:

- Semiconductor Optical Amplifier (SOA),
- tunable wavelength filter, Etalon Wavelength locker,
- Optical Add Drop Multiplexing filter (OADM) and
- variable optical attenuator (VOA).

As part of this pre-validation component campaign, the following opto-electronic components have been tested, focusing on the parameters which are considered critical for the FBG system application [10, 11] (mainly related to wavelength stability and insertion losses):

The following table summarizes the main parameters to be validated during the test sequence:

Table 1: Optoelectronic components under test and monitored parameters

Component	Parameters		
SOA	Drive current increase	TEC current increase	Gain decrease
Tunable filter	Free spectral range	Side-mode suppression	Insertion loss increase
OADM	Spectral shift		Insertion loss increase
Etalon wavelength locker	Spectral shift		Responsivity reduction
VOA	Attainable attenuation		Insertion loss increase

The selected components have been tested on the entire operating temperature range, under gamma radiation and under mechanical vibration and shocks.

Other optoelectronic components which are also used within the system, such as photodetectors, couplers or connectors have been considered to be at a greater TRL and are thus not being tested.

The results of all the tests performed as well as a description of these tests are presented in the following paragraphs.

A. TEMPERATURE CHARACTERIZATION

The temperature characterization of each optoelectronic device was performed in the temperature range from -30ºC to +70ºC. In some cases these temperatures were out of the specification of the devices, but it was considered that the integrity of the devices was not in dangerous and, however, it was interesting to know the evolution of the critical parameters of each device within this temperature range. The following paragraphs summarizes the results obtained

OADM Thermal Characterization: The samples showed very good stability during thermal characterization as shown in the following picture.

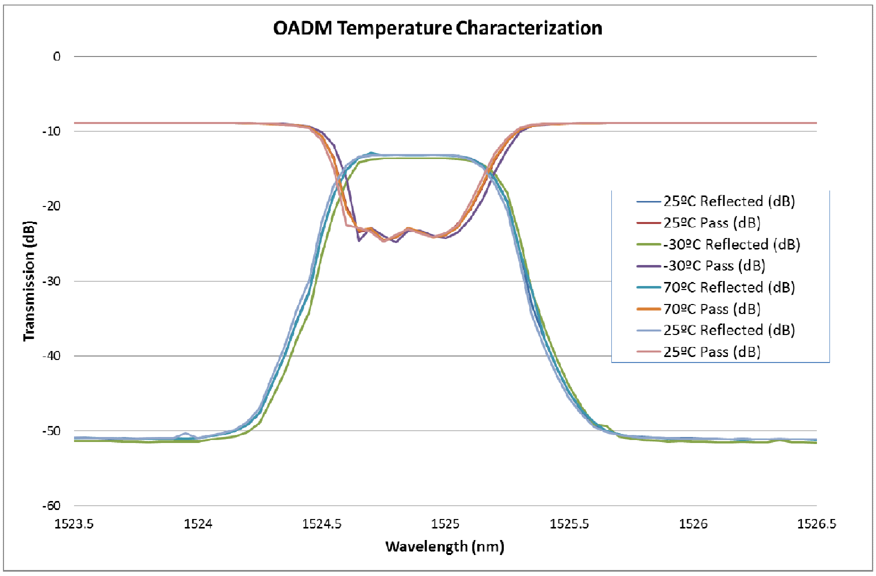

Fig. 8: OADM Temperature Characterization

Tunable FILTER Characterization: The tunable filter is a Fabry-Perot based filter tuned by changing the applied voltage. As could be expected, the filter wavelength response is quite sensitive to temperature variations. This is nevertheless irrelevant since on the interrogation unit the filter sweeping voltage is continuously controlled based on the information provided by the absolute wavelength references. As can be seen in the picture 9 insertion losses vary around 10dB on the full operation temperature range. The drops shown at 100 and 120 minutes are due to the loss of locking during the measurements, but this is only related to the test setup.

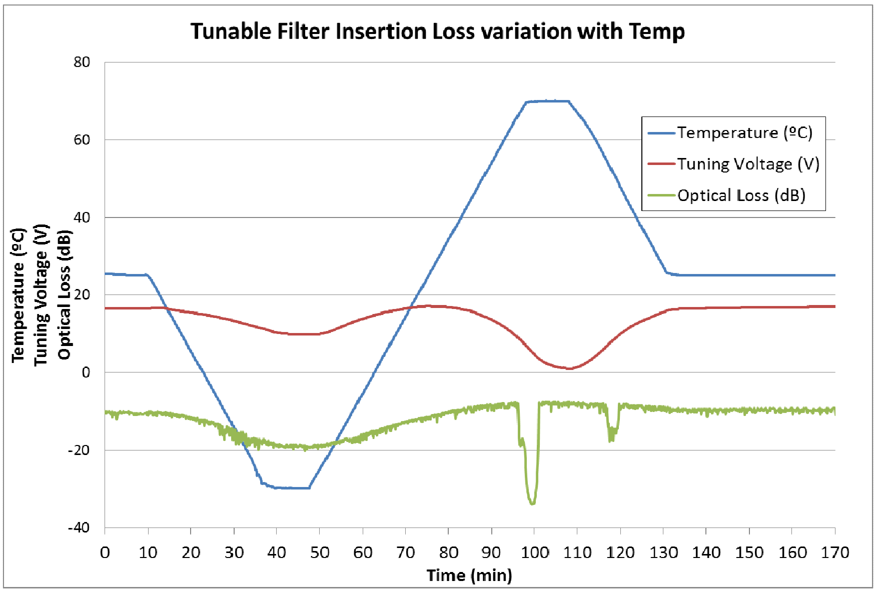

Fig. 9: Tunable Filter Optical Losses Stability with temperature

Etalon Wavelength Locker: The evolution of the etalon characteristic for an etalon maximum peak with the temperature has been measured using a Bristol 721A wavelength meter. In this case the temperature range measured was from 0ºC to 70ºC. The total variation of the wavelength during the entire temperature variation was of 5.71pm.

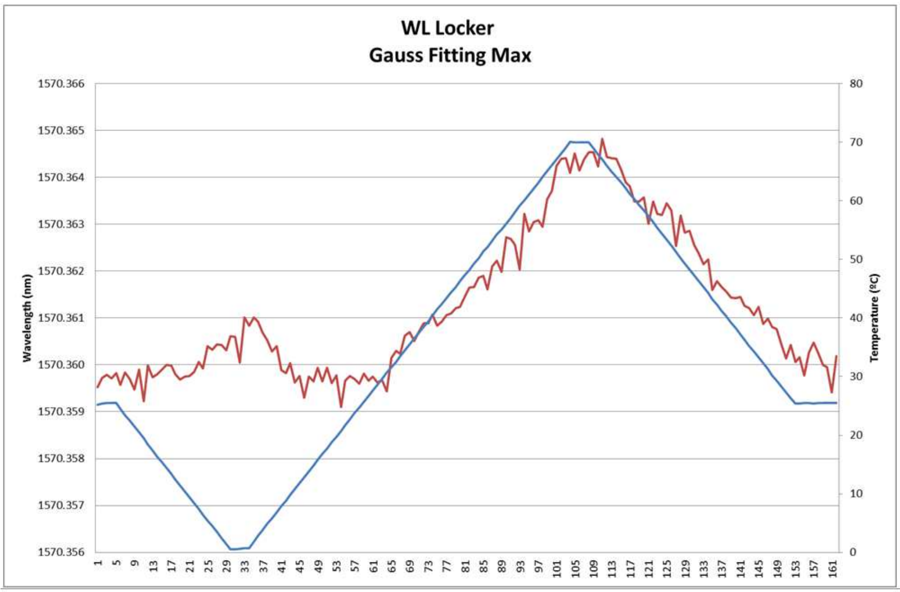

Fig. 10: Wavelength Locker Temperature Characterization

Variable Optical Attenuator: The following graph shows the attenuation variation with the tuning voltage at minimum, maximum and ambient temperature.

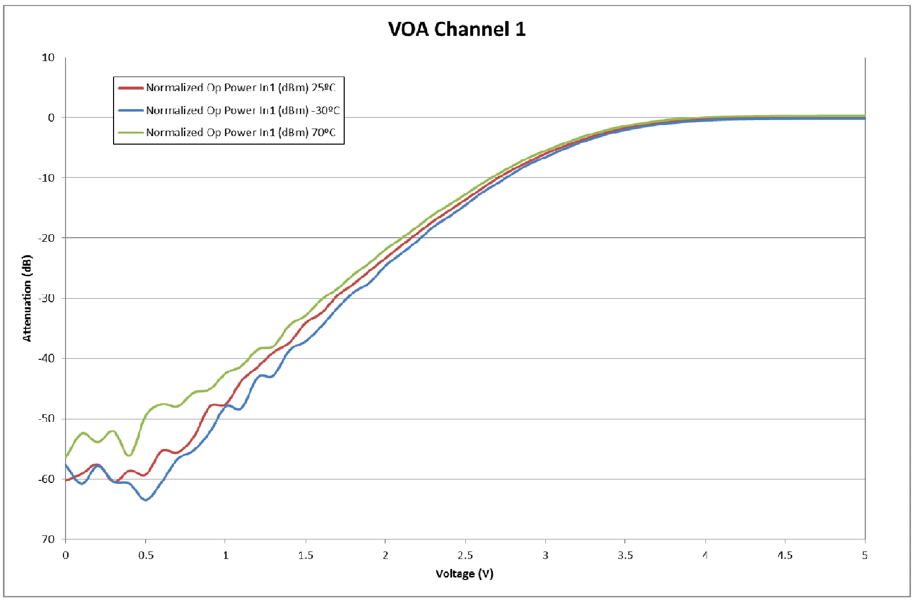

Fig. 11: VOA Temperature Characterization

The stability of the attenuation at an intermediate attenuation (2V input voltage) was monitored during the variation of the temperature. Note that the variation was lower than 0.1dB as shown in the following picture:

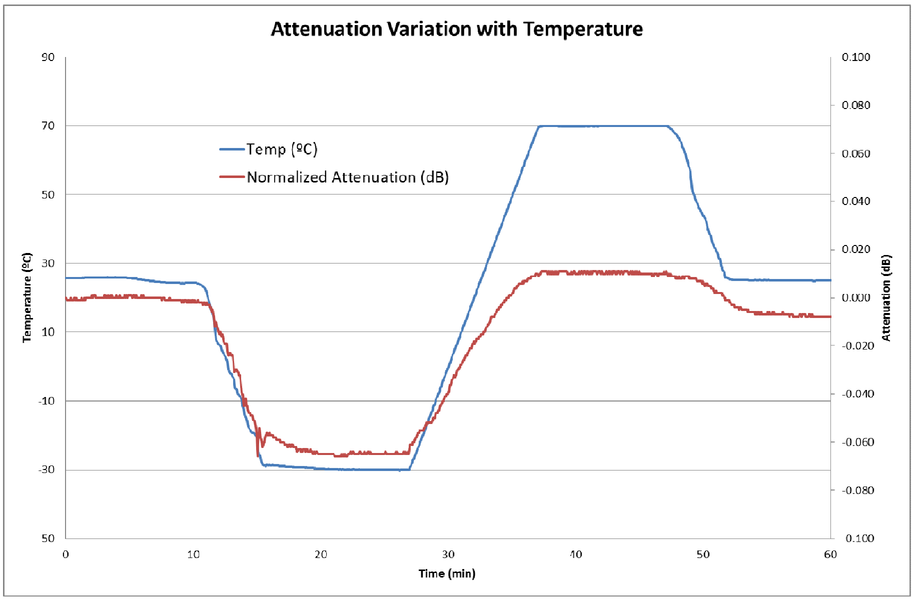

Fig. 12: VOA Temperature Stability with temperature

B. *MECHANICAL TESTS*

The samples were submitted to sine and random vibration as well as SRS (Shock Response Spectrum) shock tests according to ECSS 10-03 standard. The samples were mounted on a PCB in the same way they would be mounted in the final application. The main optical characteristic of each optical component was monitored during the vibration tests or they were measured before and after (this was the case of the tunable filter). In the same way the components were characterized before and after the SRS shocks. The following picture shows the setup used:

Fig. 13: Vibration Test Setup

The following results were obtained:

OADM Mechanical Test: No variation of the reflected or passed optical power was measured.

Tunable Filter Mechanical Test: The filter was measured before and after the vibration tests and no degradation was observed.

Etalon Wavelength Locker Mechanical Test: The wavelength locker at quadrature point was monitored during the vibration tests and measured before and after the shock tests. No relevant variations were measured.

VOA Mechanical Tests: The variation of the attenuation during vibration was less than 0.5dB. Note that the tested components are MEMS and therefore, there are moving parts that could be affected during vibration. However these components showed good mechanical properties.

C. GAMMA RADIATION

The samples were submitted to gamma radiation according to ESCC 22900 with a dose rate of 430 rad (Si)/h and intermediate steps at 10, 20, 30, 60 and 100 krad. Note that all the samples tested are COTS. The following results were obtained:

OADM Gamma Radiation Test: No variation of the reflected or passed optical power was measured as shown in the following picture:

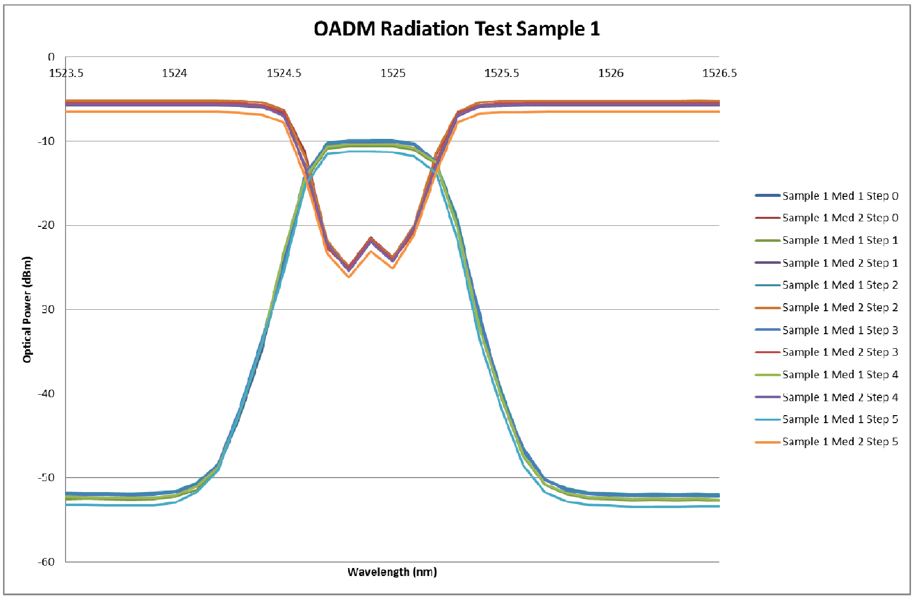

Fig. 14: OADM Radiation Test Result

Tunable Filter Gamma Radiation Test: The sensitivity of the filter to temperature variations made difficult the comparison of the measurements performed during the radiation tests. However, it was shown that no relevant degradation was obtained. Therefore, and considering the use of a control loop for locking, these filters are considered to be radiation resistance.

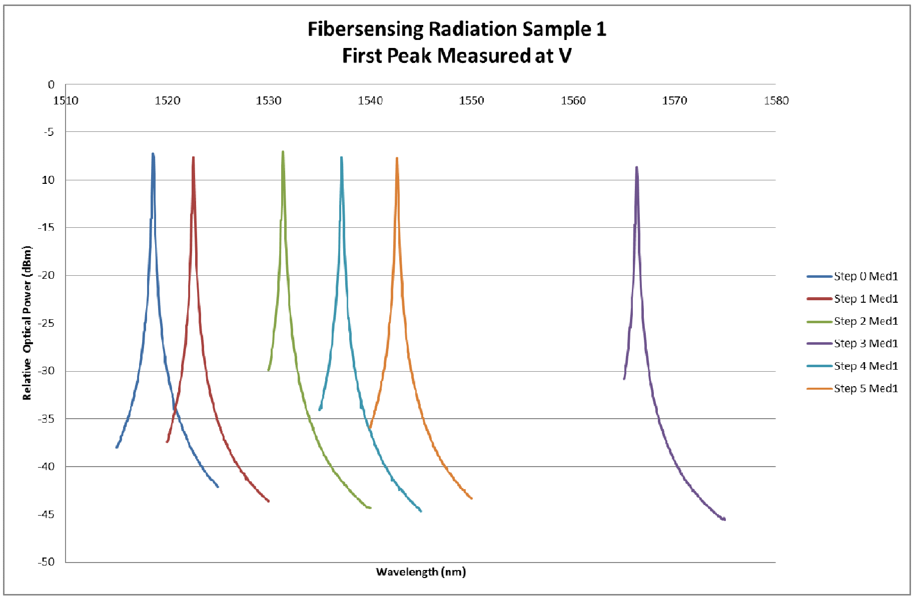

Fig. 15: Tunable Filter Radiation Test Results

<u>Etalon Wavelength Locker Gamma Radiation Test</u>: The wavelength locker at the expected locking point was characterized at each intermediated step. The samples survived the radiation test without degradation as shown in the following picture:

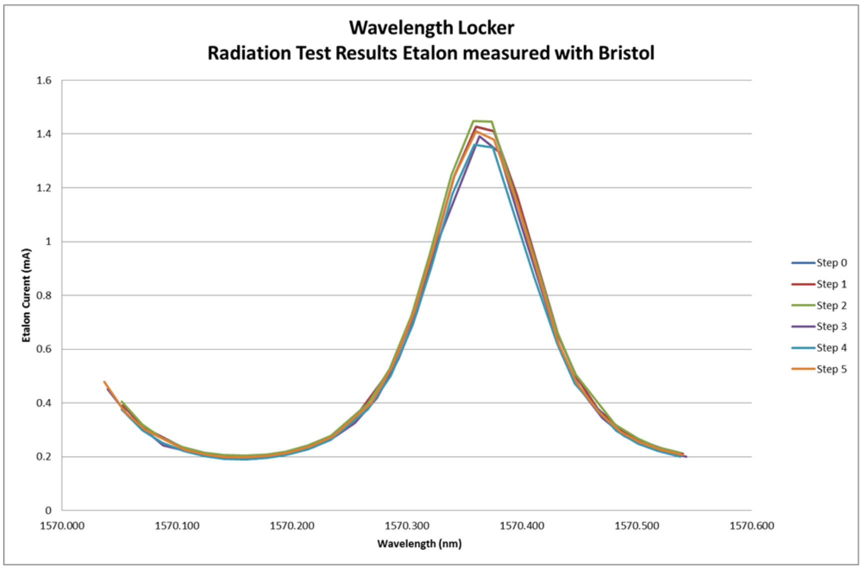

Fig. 16: Wavelength Locker Radiation Test Results

<u>VOA Gamma Radiation Test</u>: The VOA tested was the COTS version in plastic package. It was known that the same manufacturer has a radiation resistance VOA, but the plastic standard version was tested under radiation. However the non-radiation prepared VOA failed completely after 30 krad as shown in the following picture:

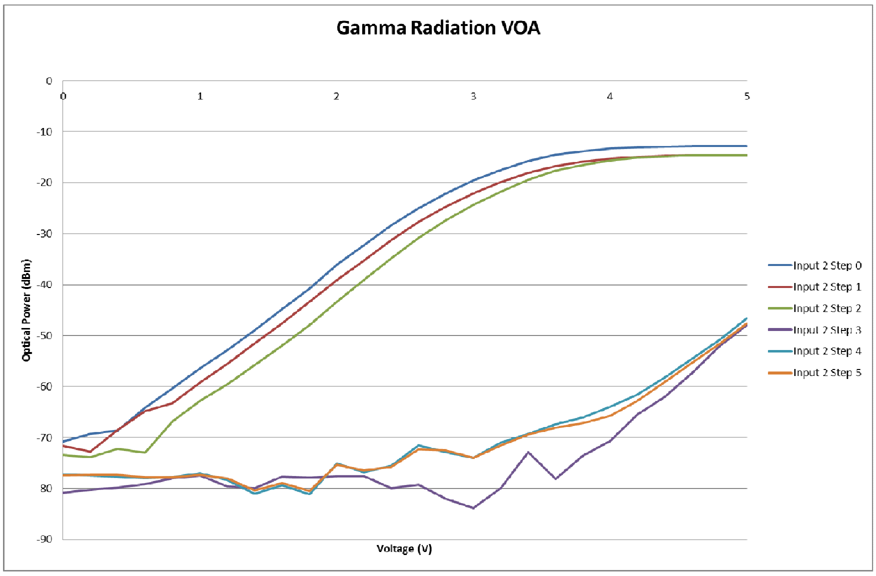

Fig. 17: VOA Radiation Test Results

FBG SENSOR PRE-VALIDATION

A new and miniaturized FBG temperature sensor design has also been provided. The sensor has been specifically designed for applications requiring small size and weight, operation over extended temperature ranges (-55 to 125ºC) [12, 13], large number of sensors and high multiplexing capability over a single fiber, dielectric materials, low outgassing and easy installation process and attachment to any kind of surface. Furthermore, the capability of using a single calibration formula for all sensors has been sought on the present design.

The sensor packaging is based on an alumina substrate, providing a high Young modulus for strain decoupling. This allows for the consecution of a small form factor (20 x 6.35 x 2mm) and low weight (1gr) sensor, while providing easy handling and good mechanical performance.

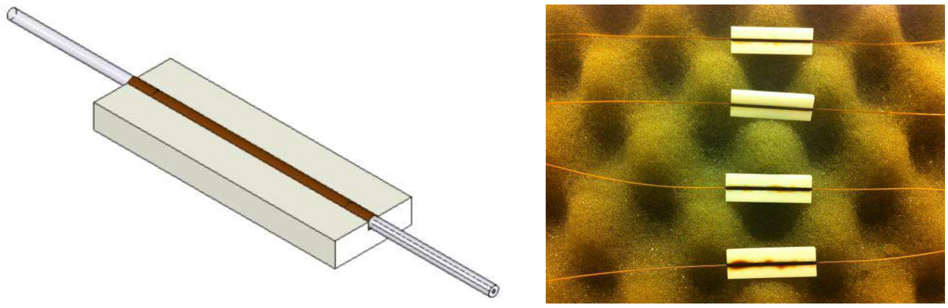

Fig. 18: Sensor virtual image and picture of 4 samples

Sensor performance has been tested on the -40 to 130ºC range both with loose sensors and with sensors attached to aluminum an substrate using Kapton tape and an epoxy adhesive (to prove strain decoupling).

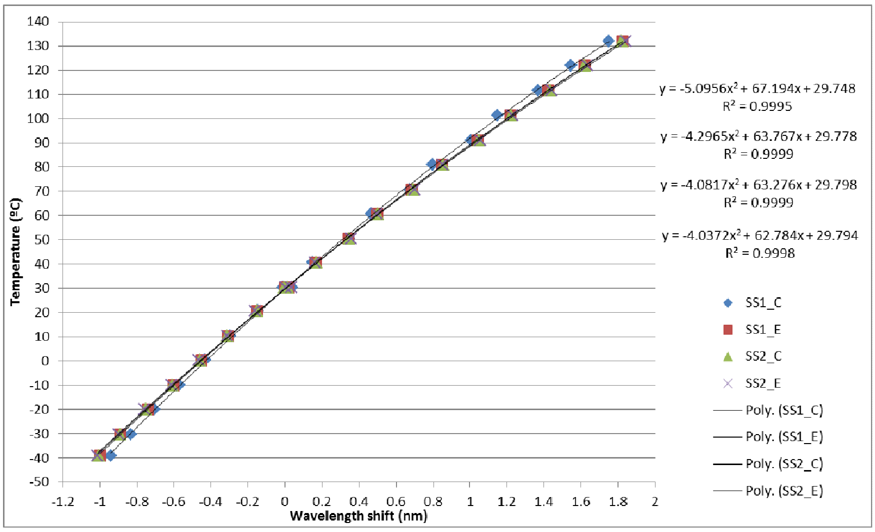

Fig. 19: Sensor temperature response from -40 to 130ºC

Sensors shown a good response over the full temperature range and with the different bonding approaches, and the employment of a single lookup table formula for all sensors and bonding procedures yielded errors lower than ±1ºC (3 samples tested).

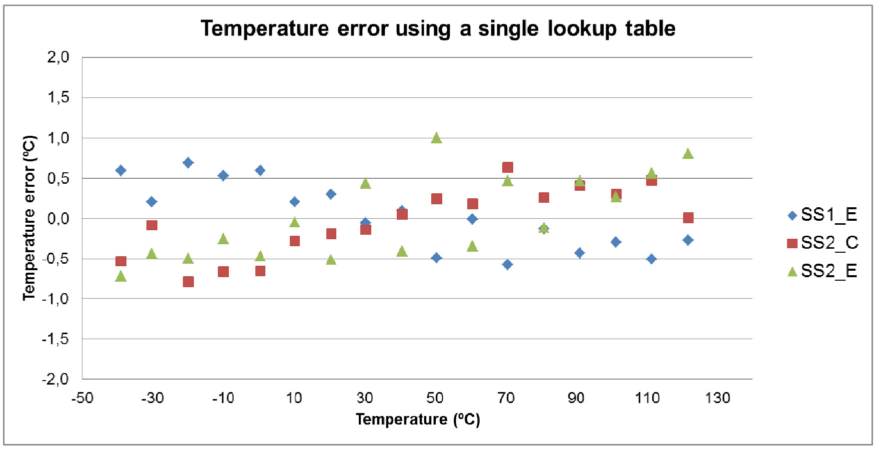

Fig. 20: Temperature error using a single lookup table

Preliminary tests have also been provided down to liquid nitrogen temperature (-196ºC), showing good performance of the design.

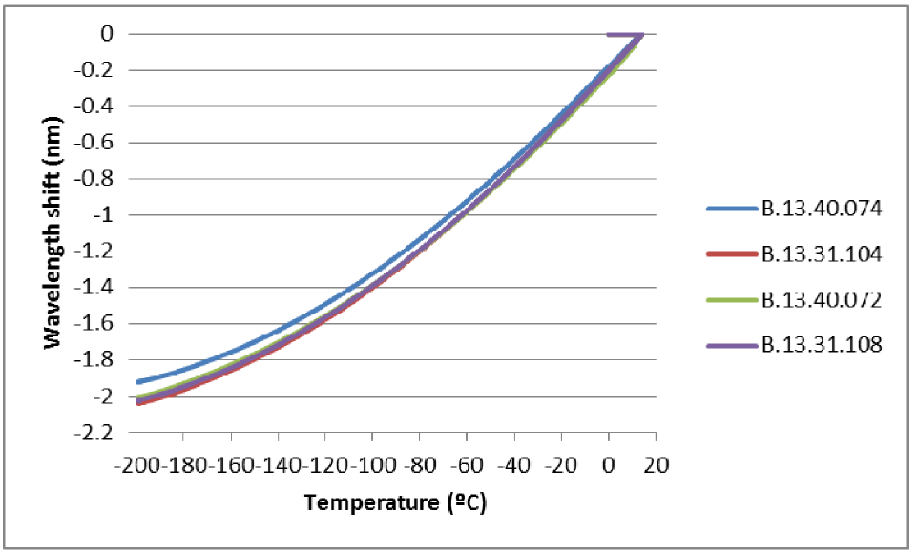

Fig. 21: Sensor response down to liquid nitrogen

Mechanical tests have also been conducted on the sensors, proving output fiber bending losses lower than 7.5mm and fiber pull strength greater than 6.5N.

CONCLUSIONS

The results obtained are very promising for the implementation of an Interrogation Unit for FBG sensors to be space validated. The main problems encountered were related to radiation of a component that is known to have a radiation resistance version. However not all the critical components have been tested yet due to delays of the manufacturer of the SOA.

FUTURE WORK

The testing of the opto-electronic components is not completed yet due to the delays of the SOA manufacturer. These tests will be done once the components are available (different suppliers are being contacted).

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