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Demonstration of the use of Fiber Bragg Grating for Optical Sensing (FIBOS) during an aerospace mission

Raquel. López Heredero, Malte Frövel, Tomás Belenguer, David Barrera-Vilar, Francisco García Quirós, Raimundo Garcia-Olcina, Joaquín, Vague, Salvador Sales

ABSTRACT

Fiber Bragg Gratings, FBG, are very appropriate strain and temperature sensors for structural health monitoring of satellite structures. They can be embedded in composite structures and monitor the entire life cycle of a satellite structure from the manufacturing process, to the mechanical and thermal certification tests, the launch loads up to the operative loads in space. The optical device based in two FBGs that will be used to measure temperature and strain during the OPTOS mission is presented. OPTOS is a picosatellite, designed and manufactured by the Spanish Institute for Aerospace Technology, INTA that will be launched at the beginning of 2009. The main goal of the mission is to demonstrate the feasibility of several technologies for space applications inside a miniaturized space and with big restrictions in terms of mass and power consumption. The paper describes the different units that constitute the FIBOS payload: a) one monolithic tunable laser used as light source offering great advantages as wide range of tunability, robustness and fast electronically operation; b) two FBGs that are mounted onto one steel mechanical structure to monitor independently temperature and strain; c) the processing unit that contains the digital electronics that processes the signal produced by the receiver unit, follows the synchronization between the laser source and the receiver and contains the electrical interface with the Electrical Power Subsystem (EPS) and the On-board Data Handling (OBDH) of the satellite.

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INTRODUCTION

OPTOS is a picosatellite developed by the Instituto Nacional de Técnica Aeroespacial (INTA) to be launched in 2009. OPTOS was born with the intention to provide an "easy" access to the space based on short development period and low costs. The main goal of the satellite in orbit will be to demonstrate its own capability as a technological demonstrator for future missions. OPTOS will orbit at a high of 680 km, Low Earth Orbit, and an inclination of 98.1º. The required lifetime is one year [1-2].

The launcher services will be provided by the California Polytechnic University (Cal Poly) at San Luis Obispo. OPTOS is based on the triple-configuration of the CubeSAT standard and uses the Poly Pico-satellite Orbital Deployer (P-POD) system offered by the Cal poly. Both, CubeSAT physical standard and P-POD deployment system have been used as design references. CubeSATs are cube shaped pico-satellites with a nominal length of 100 mm per side and the P-POD is an aluminium, rectangular box with a door and a spring mechanism. The dimensions of OPTOS are 100 mm x 100 mm x 340.5 mm and as result of the current configuration and its weight is 3.5 kg [3].

Spacecrafts systems require measurements of their status continuously to be able to operate the different payloads at the adequate environment circumstances. For this purpose, sensors based on optical fibers present several advantages as electromagnetic immunity, remote sensing, low mass of the fiber-optic cables and possibility of multiplexing with distributed sensors [4]. Among all the optical fiber sensors, Fiber Bragg Gratings (FBGs) result very appropriate since their optical response is contained in the wavelength reflected by the grating written in the core of the optical fiber by modification of its refractive index. FIBOS (FIber Bragg gratings for Optical Sensing) is the payload based on two FBGs to be used in OPTOS to measure temperature and strain during the mission. In the case of a successful performance of the FBG and the lecture equipments in space FBG could be used in future missions for structural health monitoring of the satellite structures. They can be embedded in the composite structure of the satellite and monitor the entire life cycle of a structure from the manufacturing process, to the mechanical and thermal certification tests, the launch loads up to the operative loads in space.

OPTOS will demonstrate the feasibility of optical fiber sensors for an aerospace application. As far as we know, OPTOS will be the second platform to use this technology after PROBA-2 fabricated by ESA and to be launched at the end of 2008 [5].

This paper presents the design of FIBOS, the engineering model and shows the first results obtained.

FIBOS PAYLOAD OVERVIEW

A schematic view of FIBOS is represented in Figure 1:

- The light source unit is a pigtailed tunable laser.
- The sensing unit is composed of two FBGs mounted onto a steel support.
- The receiver unit is a pigtailed PIN InGaAs photodiode (model EPM605 from JDSU).

- The processing unit integrated in one Printed Circuit Board (PCB) to control the laser, the photodetector and the communications with the OPTOS On Board Data Handling system (OBDH).

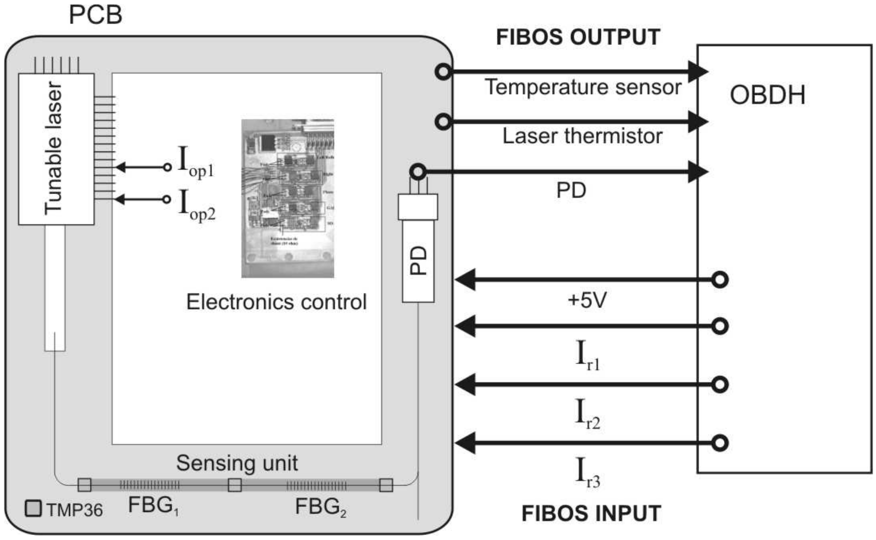

Figure 1: FIBOS block diagram: I_{ri} (electrical current for laser reflectors), I_{opi} (electrical current that controls the laser optical power), PD (photodetector).

The joint of the source, sensing and receiver units will be made via fusion-splices to create a permanent joint between all the optical fibers.

A low voltage temperature sensor (model TMP36) is integrated onto the PCB to measure the temperature and compare the data received from FIBOS.

The complete system is only 79 x 69 x 15 (height) mm in side, weighs less than 120 g and its average power consumption is less than 1W. Due to the restrictions of space, mass and power consumption in OPTOS, the procurement of the different components for FIBOS has been complicated.

According to the philosophy of OPTOS mission and to the limitations of the market itself, the use of space qualified components have not been always possible and therefore, commercial components have been chosen for FIBOS in most cases even if evaluation of the performance of these components in the harsh space environment is going to be studied, mostly in terms of gamma and proton radiation.

Light source unit

Preliminary thermal analysis of OPTOS showed great gradient of temperatures (~70-100 ºC) during the mission [6] and therefore, large shift of the wavelengths reflected by the FBGs were expected (> 2 nm) depending on the location and the material used to measure the strain. Therefore the light source used for FIBOS had to be capable of tuning a wide range of wavelengths. Besides, it is important to note that the tuning method preferred was by changing voltage or current not with temperature since a fine control of temperature inside the platform of a satellite is very complicated. Besides the optical constrains to find the suitable light source, there were some other limitations as room space, mass and power consumption as commented before.

The tunable laser chosen for FIBOS is a pigtailed module manufactured by SYNTUNE (model S3500) based on a modulated grating Y-branch design with a parallel coupling of two modulated grating reflectors. The laser is mounted with a thermistor to control the temperature using a thermo-electric cooler (TEC). The tests performed with the laser up to now shows that the power consumption is lower when cooling the laser and therefore, the temperature set point of the laser will be a bit higher than the environment temperature at the moment of the measurement during the OPTOS flight.

The output optical power depends on the value of two injecting currents that maintain the typical behaviour of the laser and provide the gain to obtain high output powers (the combination of both currents can be up to almost 300 mA). The wavelength emitted by the laser corresponds to a fine combination of three different currents (maximum of ~ 30 mA) applied to two reflectors and a "phase" area.

A calibration of the stabilization of the tunable laser in a vacuum environment is being performed at the moment and some radiations tests are programmed to study the necessity of the shielding the unit.

Sensing unit

FIBOS contains two FBGs mounted inside the groove of a steel support (see Figure 2) that will be fixed onto the PCB: FBG1 is fixed without strain and is only submitted to temperature changes (λ_1 is its Bragg wavelength) and FBG2 fixed along a cantilever with some strain and is submitted to temperature and strain of the steel changes but free of distortion of the PCB itself (λ_2 is its Bragg wavelength).

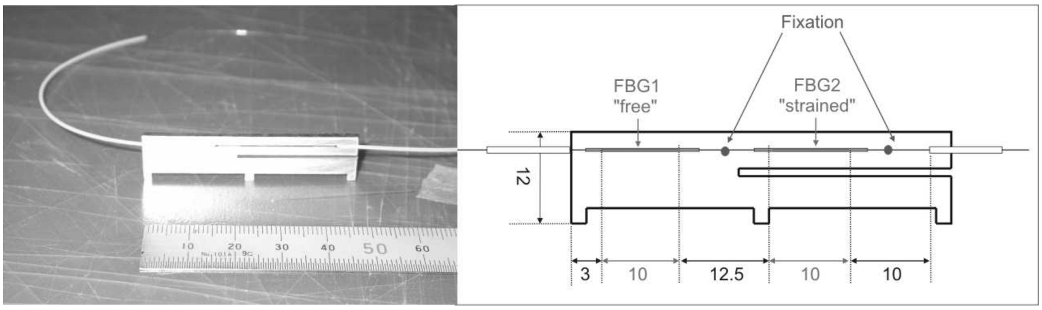

Figure 2: FIBOS sensing unit (dimensions are in mm).

All the FBGs have been fabricated by the Grupo de Comunicaciones Ópticas y Cuánticas (GCOC) of Valencia Polytechnic University with a photosentive boron doped FIBERCORE optical fiber with 125 μm outside diameter and 245 μm coated diameter by means of a frequency doubled Argon-ion laser. The two FBGs have been inscribed using the same 1070.4 nm period uniform phase mask. To create the different wavelengths of the FBGs, one of the FBGs have been prestrained. Using the continuous scan method, both FBGs have been created apodised to decrease the side-lobes and with the same reflectivity.

The FBGs will work in transmission in order to avoid the use of couplers and to facilitate the detection of the wavelengths reflected by them during the mission following this method: the tunable laser emits one wavelength, λ_e; if λ_e does not correspond with any of the wavelengths reflected by the FBGs, the photodetector will receive some optical power and will transmit some voltage through the processing unit; when λ_e coincides with λ_1 or λ_2, all the light is reflected and the photodetector won't receive any significant signal. This moment will be detected by the OBDH and from the calibration data it will be possible to convert it into temperature. Therefore, during the flight, it will be necessary to tune the laser at several wavelengths until the photodetector signal is zero. This action will be performed via the OBDH by sending packages with combinations of the three reflectors currents necessary to tune finely the laser.

The calibration work concerning the wavelength emitted by the laser to tune the FBGs at different temperatures is being performed at the moment inside a thermal vacuum-chamber. The result of this work will build the matrices of electrical currents to be sent during the OPTOS flight where the reference of the *in situ* temperature will be measured by the standard thermocouple.

Processing unit

The processing unit contains the electronics to supply processes the signal produced by the receiver unit, follows the synchronization between the laser source and the receiver and contains the electrical interface with the electrical power subsystem and the OBDH from OPTOS.

The tunable laser, the sensing unit and the photodetector will be mounted on the PCB and directly integrated in OPTOS as an independent subsystem linked only via electrical connections.

The processing unit receives 5 V supply form OPTOS that is used to activate the TEC to control the current performance of the laser. The DC-supply is also used to activate the photodetector and to provide enough current to the laser to emit enough output optical power. Besides, the OBDH generates three independent 10-bit digital signals. These signals are fed into D/A converters and then used to tune the wavelength of the laser by the control of the currents of the reflectors and the “phase” area. The OBDH works with a clock basis of several MHz.

The processing unit will send the output voltage of the photodetector to the OBDH for each combination of the reflector currents to be able to detect the moment at which λ_e coincides with λ_1 or λ_2 and then, convert the data into temperature. Every time, the voltage from the thermocouple is also sent to the OBDH to have a reference of temperature.

FIBOS GROUND CALIBRATION

Two sensing units have been fabricated for the engineering model. Taking into account that the sensitivity of the FBG to temperature and strain are typically 8 pm/ºC and 1.12 pm/με and considering the thermal expansion coefficient of steel as 11 με /ºC, the FBGs have been fabricated in the laboratory 0.5-0.6 nm apart and will be mounted with a separation of ~1.5 nm after mounting the FBG2 with some tension in order to reduce as much as possible the range of wavelengths to be tuned with the laser but also to guarantee the lack of overlapping under the most extreme conditions of temperature (ΔT= 40ºC).

The ground calibration has started with the characterization of the wavelengths reflected by the FBGs with temperature inside a thermal calibrator and monitored with a laptop and analogue input cards. The temperature of the calibrator was automatically cycled with a hold time of 10 minutes at each temperature level with a guarantied temperature stability of better than 0,1ºC. The test was performed between -10 to 30 ºC, 8 times each cycle and measurements have been taken every two seconds. The temperature tests with the sensing units yielded the results shown in Figure 3.

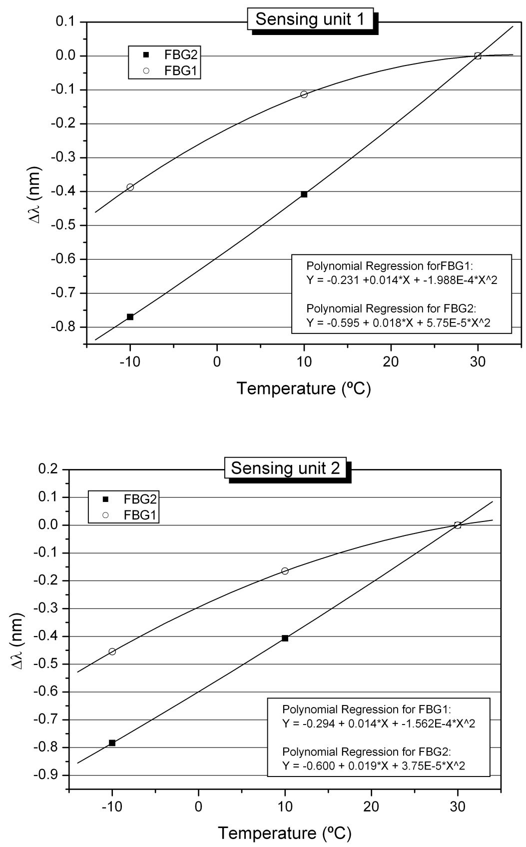

Figure 3: FBGs reflected wavelength shift (Δλ) dependence with temperature taking as reference the wavelength at 30 ºC.

It is important to note that the standard deviations for the strained FBG (FBG2) result smaller than the one obtained for FBG1; the FBG2 results fit better a linear regression. This is due to the mechanical interactions between the teflon jacket of the FBG and the steel structure and this will be taken into account for the flight model. The standard deviation of the 8 times repeated temperature cycles is better than ±0,2ºC for the strained FBG and about ± 1ºC for the free FBG.

The current OPTOS thermal analysis shows that the temperature of FIBOS during one orbit will oscillate between -5 and 20 ºC. The calibration of the stabilization of the wavelength emitted by the tunable laser at different temperatures when the set point temperature of the laser is 25 ºC are being performed at the moment in a thermal-vacuum chamber. The ground calibration of the laser together with the sensing unit is necessary to create the combination of electrical currents to tune the laser during the mission. These tests in vacuum will also give information about the best way to control the temperature of the laser (need of use of radiative thermal straps or not) and about the time needed to warm-up and stabilize the laser for the operation mode during the flight since FIBOS will be intermittently activated to minimize power consumption.

As it was commented before, it is necessary to study the performances of all the optical devices inside the harsh space environment, mostly due to radiation. The estimated total dose accumulated during OPTOS mission of one year is 10 krad. Some FBGs with different jackets (acrylic, ormocer and polyimide) have been irradiated up to 10 krad gamma radiation with a cobalt source inside a swimming pool. The difference between the wavelengths reflected by the FBGs before and after the radiation test at 24 ºC is less than a few pm in all the cases even if further analyses are to be completed. Gamma and proton radiation tests of the tunable laser and the photodetector will be completed with this year.

CONCLUSIONS

FIBOS represents a novelty since it is the second experiment based on optical fibers to be launched in a spacecraft as a payload of the OPTOS picosatellite and aims to evaluate the use of optical fiber sensors in aerospace missions.

FIBOS has been designed, all the critical optical devices meeting the restricted specifications have been chosen and procured, and the engineering model has been already fabricated.

The sensing unit containing two FBGs has been tested at different temperatures and has passed successfully the gamma radiation test. The engineering model is ready to be calibrated in a thermal-vacuum chamber to elaborate the combination of electrical currents needed to tune the laser during the flight. This ground calibration constitutes a highly important phase since the data extracted from the laboratory will define the electrical and the thermal interfaces and the software needs to control the operation of FIBOS during the OPTOS mission.

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