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PHOTONICALLY WIRED SPACECRAFT PANELS – AN ECONOMIC ANALYSIS AND DEMONSTRATOR FOR TELECOMMUNICATION SATELLITES

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ABSTRACT

In this paper we present the design of smart satellite panels with integrated optical fibers for sensing and data communication. The project starts with a detailed analysis of the system needs and ends with a demonstrator breadboard showing the full performance during and after environmental tests such as vibrations and temperature.

Future science missions will need higher bandwidth in the Gbit/s range for intra-satellite communications, so the step from electrical transmission media towards fiber-optical media is the logical next step to cope with future requirements. In addition, the fibers can be used to monitor temperatures directly underneath satellite payloads which will reduce the integration effort in a later phase. For temperature monitoring so called fiber Bragg gratings (FBGs) are written in special radiation tolerant fibers, which reflection wavelength allows a direct link to temperature at the grating position. A read-out system for FBGs to use within satellite applications is currently under development at OHB.

For this study, first the environmental requirements for the panels are derived and in a second stage the functional requirements are defined. To define the functional requirements a telecommunication satellite platform, in the case here the Small-GEO series from OHB, has been taken as baseline. Based on the configuration of temperature sensors, communication lines and electrical signaling a possible replacement by fiber-optical technology was defined and traded w.r.t. its economic benefit.

It has been pointed out that the replacement of temperature sensors will reduce harness mass, but the great benefit is seen here in the reduction of assembly effort. Once the satellite panel is manufactured, the temperature sensors are already implemented at certain positions. Another point for mass savings which has pointed out is the replacement of the high-voltage or high-current high power commands (HPC) by fiber optics. Replacing some of the several hundred of required HPC lines with very light-weight fibers would reduce the HPC harness by some tens of kilograms. A detailed table illustrating the mass savings and also the integration time savings will be presented in the paper.

To keep the track on an economic solution also a detailed market research was carried out to find suitable components for fiber-optical connectors, fibers and protections buffers. Specially for the connectors a solution based on military qualified connectors pointed out to be the most interesting solution in terms of price and functionality, especially when using multi-pole connectors.

The project closes with the construction of a breadboard demonstrator consisting of three different panels, one large panel (ca. 1 m²) and two smaller panels (ca. 0.3 m²). The large panel and one of the small panels are made out of aluminum facesheets whereas the other small panels is made out of CFRP.

I. ANALYSIS OF SYSTEM NEEDS

The target of this analysis is to find out the possible signals which can be replaced by fiber optical sensing. First of all, the technology aspect must be taken into account which signal can be replaced and further which signals make sense to be replaced in an economic way. A summary of the signals and the possibility of replacement is given in Table 1.

Table 1: Possible signals which could be replaced by fiber-optical signaling

Signal type	Can be replaced?	Should be replaced
Analog Signal Monitor (ASM)	Potentially yes Seen critical due to performance degradation because of radiation impact of fiber transmission and optical output power. So the value could be decalibrated over life time.	NO
Temperature Sensor Monitor (TSM)	Yes With FBG Sensors.	YES
Resistor Monitor (RSM)	Not possible. Resistance is the changing parameter, this cannot be monitored by fiber-optical sensing.	NO
Bi-Level Switch Monitor	Not directly Only possible when an optical switch is introduced in the peripheral equipment which is seen as an non-economic solution.	NO
Current or Voltage Sensing	Potentially yes Could be possible but not in an economic way inside a satellite.	NO
High-Power Commands (HPC)	Potentially yes Changes in equipment might be necessary	YES
Data transmission	Potentially yes Changes in equipment might be necessary	YES For high speed datalinks or highly sensitive date lines

In addition also the number of signal lines is important to validate if a replacement makes sense or not. The rough number of signal lines for a telecommunication satellite is given in Table 2 taking into account only the signal types which can be replaced by fiber optical technology.

Table 2: Number of signal lines for a telecommunication platform, estimation

Signal type	Number of Lines	Comment
Temperature Sensor Monitor (TSM)	~ 500	
High-Power Commands (HPC)	~ 2000	Will not be demonstrated in BB
Data transmission	~ 20	Depending on mission, for telecommunication satellites mostly not necessary.

II. FUNCTIONAL REQUIREMENTS TO PANELS

The overall target of the panel demonstrator is to prove the concept of the integration of FBG sensors inside the panel for temperature monitoring and additional fibers for communication purposes.

The goal of the breadboard demonstrator is divided into different sections:

- Demonstrate the functionality with components and processes which can be further extended to space missions. The component selection takes the advantage of parts used in military applications with similar environmental conditions such as vibrations, temperatures and shock loads. The designed breadboard shall be able to sense temperatures at multiple positions with FBG sensors implemented directly in the panel and it shall be able to allow a fiber-optical data communication. For this only the fiber is implemented. Designing of a transceiver is out of scope in this project. The system will afterwards be tested against temperatures and vibration loads to prove the concept.

- It shall also be demonstrated how much mass can be saved by using a fiber-optical sensing concept instead of the point-by-point wiring of the temperature sensors. For this a state-of-the art (SOA) telecommunication satellite is analysed and the mass savings are estimated.

- A possible replacement of the High Power Commanding (HPC) harness could be done by optical remote powering/switching concepts but this is not planned in the current phase.

- An estimation of AIT time will be carried out for both systems to estimate the overall savings taking both effects into account, the reduced mass and the maybe longer AIT time during panel manufacturing.

- Concerning the test philosophy the BB shall be tested against local temperature variations to prove the functionality of the temperature measurement subsystem and the full assembled and connected system (three panels and two interconnecting patch cords) shall be tested against vibration.

III. COMPONENT SELECTION

For the project here some points where initially clear such as the usage of FBG sensors for temperature monitoring [1] and the need for a mechanical transducer for strain decoupling, see also section IV.B.

The identification of a suitable connector for the target application was not an easy task, here a compromise between cost and functionality must be made. On the one hand a space qualified connector is necessary for which until the current date no released specification is available, on the other hand a cost efficient multi-pole connector is necessary to lower integration time and cost per connection. For the demonstrator design the connectors from Glenair (GFR connectors) are selected, they are available in a DSUB 25 shape and offer up to eight single-mode connections. Some pictures of the used connector are given in Figure 1.

Figure 1: GFR fiber-optical connectors from Glenair, pictures taken from datasheet.

The selected components for the project here are summarized in Table 3. The TRL levels are assumed due to the lack of qualified components or detailed test date. Nevertheless the components have been well analysed and cross checked if the can survive the thermal and mechanical loads for the demonstrator. Due to this reason also lots of commercial 'cheaper' components are not taken for the final design.

Table 3: Selected components for the different subsystem functions.

Component	Selection	TRL	Comment
Temperature Sensor Technology	FBG written by fs-IR laser	6+	Used also in commercial system, for Space app. also in Proba-V
Fiber-Optical Connectors	Glenair GFR series	6	MIL-STD tested multipole connector
Transducer	In house designed	5	
Patchcord Cable	STFOC Non-Kink 1.65mm	6	Used in NASA and submarine applications.
Internal Cables	Pure-silica core fiber in PTFE buffer	6+	For protection of the 250um thin fibers during integration and assembly.

IV. FIBER-OPTICAL SENSING

A. Temperature Sensing with FBG sensors

The selected technology for fiber-optical temperature sensing is based on so called Fiber-Bragg Gratings (FBG) sensors. The preferred wavelength of the gratings lies in the telecommunication C-band between 1528 nm and 1568 nm. In this wavelength range lots of commercial components are available not only for sensing but also for data transmission. For this wavelength also radiation hard fibers are available. The radiation induced loss (RIA) is a very important parameter for the use of fiber optics in space for long term mission such as for telecommunication satellites.

By knowing the Bragg wavelength, the temperature at the FBG can be determined. The Bragg wavelength is located where the highest reflected light intensity is assumed. Therefore a peak find algorithm, e.g. a fit function, is applied to the measured FBG spectrum. In general the reflected spectral response is used to evaluate the Bragg wavelength hence the spectrum shows a high intensity and so a high Signal-to-Noise (SNR) ratio in the area of the Bragg wavelength.

As mentioned before, the Bragg wavelength depends on the temperature at the FBG sensor. In Figure 2 on the left an FBG spectrum at 26 °C and 46 °C is measured by a interrogator system based on a tunable laser system. Hereby the spectrum moves toward higher wavelengths at ascending temperatures. In the case the characteristic tuning curve and the Bragg wavelength ($\lambda_{B1}/\lambda_{B2}$) of the FBG is known the FBGs temperature (T_1/T_2) can be estimated. The slope of the tuning curve depends on the FBG material and lies in general within a range of (10±4) pm/°C.

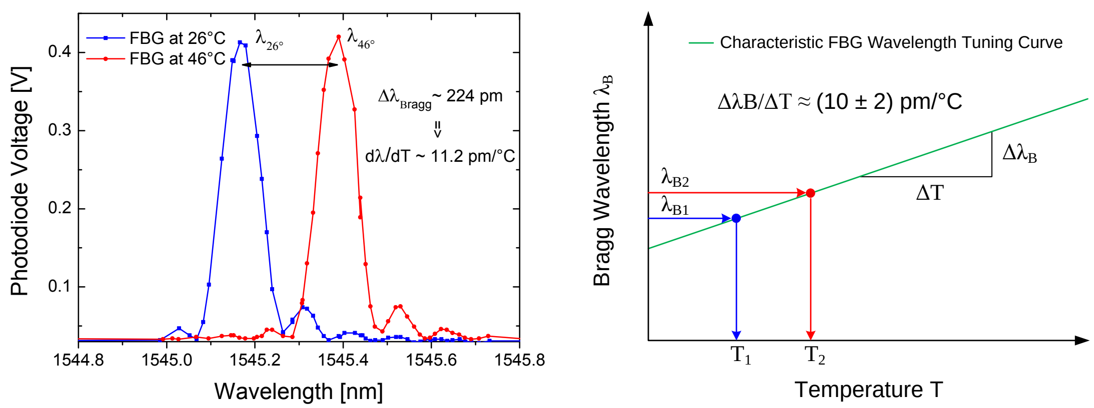


Figure 2: Measurement of an FBG spectrum at two different temperatures (left) and a scheme of a characteristic Bragg Wavelength vs. Temperature tuning curve (right).

The effective refractive index and the grating period are affected by changes in temperature. The Bragg wavelength regarding to temperature changes ΔT can be written as:

$$\lambda_B(\Delta T) = 2\left(\overline{n_{eff}} + \frac{\partial \overline{neff}}{\partial T}\cdot\Delta T\right)\left(\Lambda + \frac{\partial\Lambda}{\partial T}\cdot\Delta T\right) \quad (4\text{-}5)$$

Hereby it is assumed that no strain is applied to the grating. However in real FBGs it is difficult to decouple strain and temperature. To maintain strainless temperature measurements, the FBG is located within a mechanical package. The shift in Bragg wavelength is defined as follows (without strain):

$$\Delta\lambda_B = \lambda_B\left(\alpha_\Lambda + \alpha_n\right)\cdot\Delta T \quad (4\text{-}6)$$

Where α_Λ is the thermal expansion coefficient for the fiber and α_n is the thermo-optic coefficient. The thermo-optic coefficient at room temperature for a fused silica fiber amounts to $8.5\cdot10^{-5}\ K^{-1}$ and for the thermal expansion coefficient to $0.55\cdot10^{-5}\ K^{-1}$. It is obvious that the refractive index change shows the strongest impact regarding to the Bragg wavelength shift.

B. FBG Transducer Design

The aim of the transducer is the decoupling of strain and temperature which both affect the Bragg wavelength shift of the grating. In the project here temperatures only shall be measured, so the influence of the strain shall be cancelled out. This shall be done by an intelligent mechanical design. No electrical compensation signals or sensors shall be used. The measurement of FBGs in polarization maintaining fibers is noted here for reference only [2] but it is not considered as option due to the needed complex interrogation system. Basically four different topologies are possible which are described in more detail in the following section:

- Pure grating glued to the panel
- Feedthrough based transducer
- Capillary based transducer

The different transducer topologies are graphically illustrated in Figure 3.

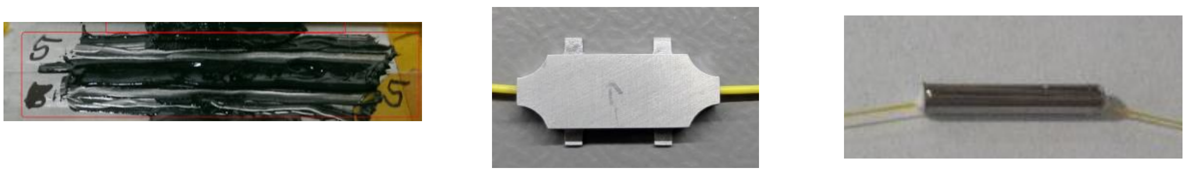


Figure 3: Left: pure FBG glued onto panel plate. Middle: Feedthrough based transducer. Right: Capillary based transducer.

The pure FBG sensor glued onto the plate needs the smallest amount of integration time whereas the feedthrough transducer needs more time due to the different pre-assembly steps needed for this option. The capillary based transducer, shown on the right side of Figure 3, is a more experimental solution. The idea was to combine the effects from low integration time of the pure FBG sensor with the strain decoupling of the feedthrough based solution.

A four point bending test was done with the designed feedthrough transducer (red curve, rectangular markers) and the pure sensor (blue curve, karo markers) glued to the aluminum plate, the results are given in Figure 4. As can be seen the transducer is necessary to compensate for the strain-induced Bragg wavelength shift. The transducer has a sensitivity to plate deflections of 0.8 pm/mm, in reality deflections larger than 1mm will not occur for honeycomb satellite panels.

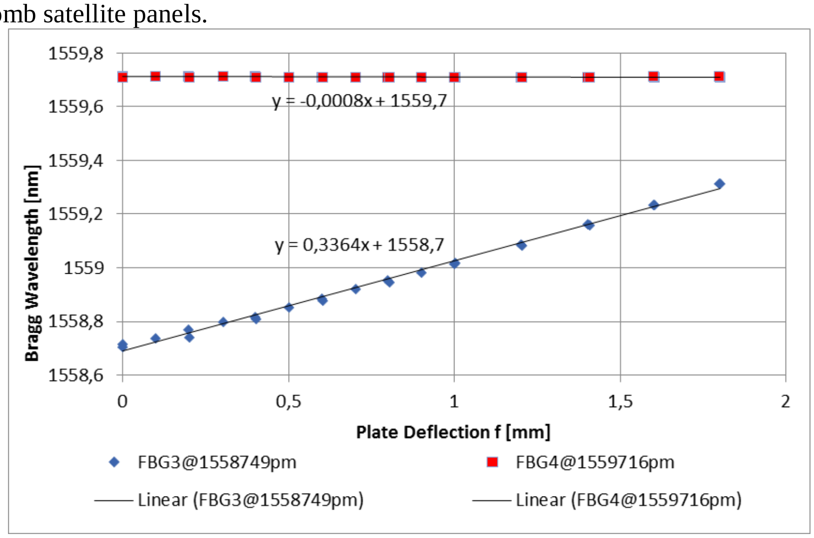


Figure 4: Measurement results of the four-point bending test for the pure FBG glued onto the plate (blue curve) and for the FBG mounted inside the special designed transducer (red curve).

V. DEMONSTRATOR DESIGN

After the functional requirements for the panel were identified, the possible components were selected a concept was established. The concept here foresees the setup of three different panels, a large one (900 mm x 800 mm x 25 mm) and two smaller ones (280 mm x 280 mm x 25mm). The interconnection scheme is illustrated in Figure 5. Each panel holds at least two strings equipped with FBG sensors (blue channels) and two strings for data communication (yellow channels).

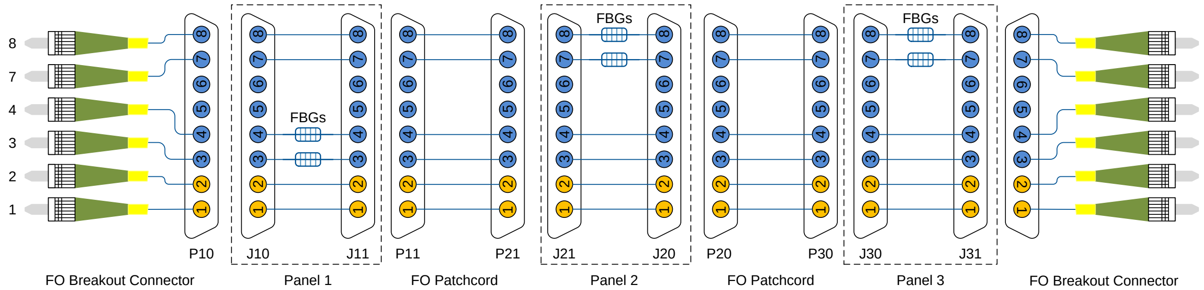


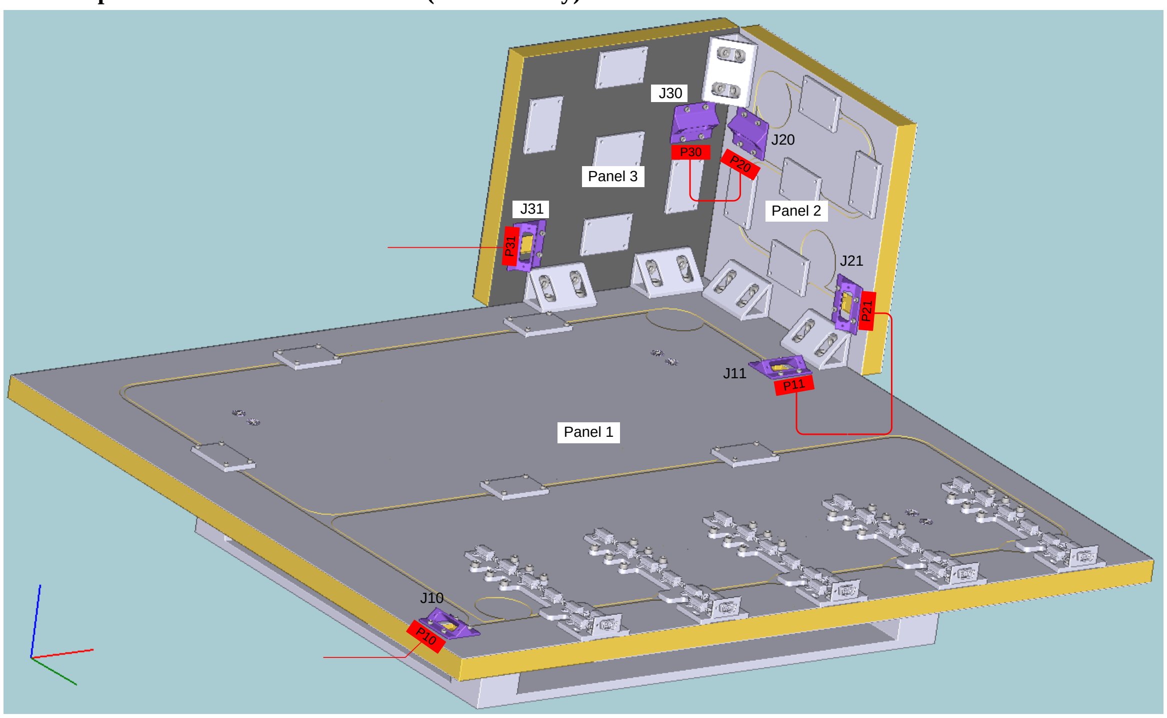
Figure 5: Illustration of the planned harness shown for the panel internal wiring and the patchcord connections.

For the satellite design a maximum sensor density of 41 sensors/m² resulted, so for the demonstrator the small panels are equipped with up to 10 sensors resulting in a total density of 127 sensors/m² which is much larger than in reality needed. However the aim of the project is here to demonstrate the possibilities of the technology. For the large panel 20 FBG sensors are foreseen, 10 sensors for each string. So in total the demonstrator is able to implement 40 FBG sensors for temperature monitoring.

As an additional demonstration also the interconnection between different panels with special manufactured patchcords is shown. For the demonstrator patchcord lengths of 0.5m are defined, the fiber itself is a single mode fiber protected with LCP buffer with an outer diameter of 1.65mm.

The 3D CAD model of the panel demonstrator is illustrated in Figure 6. The two smaller panels are mounted onto the large panel in an angle of 90° and fixed together with L-profiles. The fiber-optical connectors are mounted with an angle of 45° with respect to the panels, the corresponding plugs are connected afterwards. Also indicated in the 3D model is the internal routing of the fibers and the dummy heaters. The dummy heaters on one side of the panels are comparable in dimensions with the traveling wave tube amplifiers (TWTA) used in telecommunication satellites.

Figure 6: CAD model of the panel demonstrator, illustrating the L-profiles for mounting the panels, the three different panels and the interconnections (schematically).



VI. ESTIMATED SAVINGS IN TIME AND MASS

For the estimation of the mass and time savings first some constrains must be set. Here a telecommunication platform was analysed with the numbers of interfaces as given in Table 2. The time needed for each sensor is determined by the use of data from the OHB manufacturing personal and includes time for documentation and time for hardening of the glue. For the FBG sensor it is assumed that the sensor comes pre-assembled to the AIT personal, the time for manufacturing a single FBG transducer was tested to be approx. 15min. The final overview of the mass and time savings is illustrated in Table 4.

For the HPC system in the current architecture a lot of harness mass could be saves. This implies some modifications in the units, because of a change in physical signal property from current/voltage to light. The additional advantage which comes with the fiber-optical HPC system is the inherent galvanic isolation by the fibers.

Table 4: Mass and time effort for the classical electrical system and for a replacement with fiber-optical systems.

Parameter	Electrical		Fiber-Optical		Benefit Factor
	Mass	AIT Time	Mass	AIT Time	
High Power Com. (HPC)	224 kg	n/a	37.7 kg	n/a	5.9 (mass)
Temp. Sensing (TSM)	16 kg	1.25 h/sensor	2.6 kg	55 min/sensor	6.2 (mass) 1.4 (time)

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