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Influence of adhesive and application method on FBG temperature sensors for space applications

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Abstract— **Fiber optic sensors are already used in many industries, such as oil & gas and infrastructure. However, optical solutions have recently been explored in the aerospace sector, and Fiber Bragg Gratings (FBGs) are the most relevant sensor type. FBG sensors are a growing market, with a projected market value growth in 2028 of $5167.4 million and a compound annual growth rate of 23.9 %. Their peculiar properties (small size, lightweight, immunity to electromagnetic fields, multiplexing capability, and fast response) can overcome many of the challenges presented by the space environment. Nonetheless, they are not common in aerospace applications. With the proper packaging, FBG sensors are suitable for many thermal and chemical sensing measurements. Furthermore, with suitable packaging, FBGs could be used in aerospace since they can reach cryogenic temperatures and have vacuum applications. In this work, the effects of the adhesive and the application method on the substrate for thermal sensing were examined in a vacuum in the -170 to 220°C temperature range. The campaign test was divided into three phases with different methodologies, analyzing the eventual disturb introduced by the bonding technique. When an effective strategy is adopted, the study confirmed that, in vacuum, FBG sensors could reach comparable results with traditional thermocouples at cryogenic temperatures. This, combined with the above-mentioned optical fiber advantages, proves FBG to be strategic for thermal testing in space.**

Keywords— FBG, Fiber Bragg Gratings, Optical fibers, Distributed optical sensing, thermal measurements, Aerospace, prognostics, smart sensors, adhesive.

I. INTRODUCTION

Optical fiber is a glass and polymeric material which is able to transmit an optical signal through itself. In the last decades engineering applications based on this technology have rapidly increased their importance, also including really different sectors [1], [2]. The gamma of optical fiber applications has been augmented not only thanks to its capacity of data transmission, but also thanks to the possibility of embedding optical sensors directly inside the fiber itself [3]. Fiber optic sensors are already used in many industries, such as oil & gas [4]and infrastructure [5]. Optical solutions have recently been explored in the aerospace sector, and Fiber Bragg Gratings (FBGs) are the most relevant sensor type [6]. They are a growing market, with a projected market value growth in 2028 of $5167.4 million and a compound annual growth rate of 23.9 % [7].

The advantages of FBGs are strictly correlated to the physical features of the optical fiber itself and they are summarized in Fig. 1.

These peculiar properties can overcome many of the challenges presented by the space environment. There is also an advantage on the technique to monitor the system. Optical fiber sensors do not require continuous interrogation, thus requiring low power per sensor [2]

In recent years, some studies tried to employ FBG for space monitoring systems [6]. However, nowadays there is not available a specific “best practice” regarding the sensors fixing strategy.

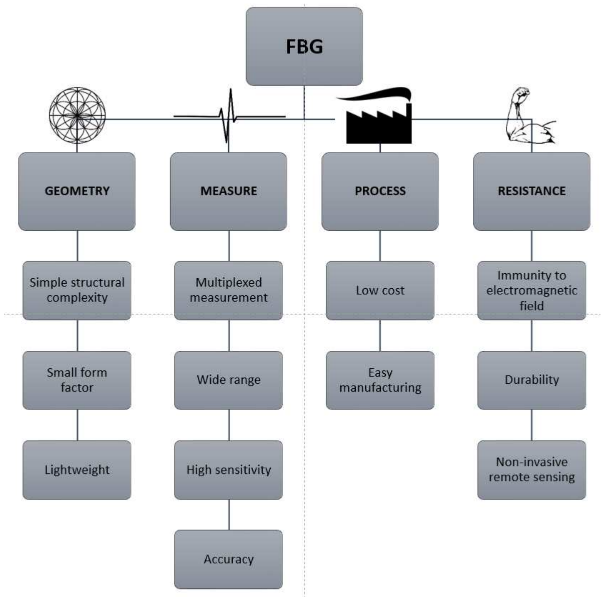

Figure 1. Fiber Bragg gratings characteristics [8]

The influence of adhesives has been studied for strain sensing with different adhesives and joint methods [9]–[12] but there is a lack of studies for temperature sensors in extreme environments. Studies on the different behavior between optical fibers made with different materials and coatings shows how important is to know the temperature sensitivity changes at cryogenic temperatures [13].

In this work, the great importance (in terms of effects on the optical outputs) of the FBGs fixing strategy is analyzed for thermal test in vacuum for space applications. Having a precise knowledge about how the adhesive could affect sensors' data is crucial both to increase the measures accuracy and to standardize the calibration process for industrial applications.

The FBG sensor is a trait of optical fiber in which the refractive index of the core underwent a periodical remodulation [14], [15]. The so generated structure (called *Bragg grating*) reflects a specific wavelength of the light beam coming through the fiber, according to:

$$\lambda_b = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the modified refractive index and Λ the grating period. The optical output of the sensor is so correlated to the physical distortion imposed to the grating by thermal or mechanical loads, according to the general formula:

$$\Delta\lambda = K_T\Delta T + K_\varepsilon\Delta_\varepsilon \tag{2}$$

Since, in average, the refractive index is between 1.4 and 1.5, and that Bragg gratings are inscribed on a single mode fiber's core, the period L is typically from 0.5 µm to a few µm to arrange the Bragg wavelength in a region of interest for detection and sensing [16]

Standard gratings can be used up to 450°C but special gratings can be inscribed to reach 800°C [17]. Sapphire fibers can be inscribed with femtosecond laser to reach over 1750°C [18]

The typical temperature sensitivity of commercial FBGs is about 10 pm/ °C but this value can be increased by using special pre- and post-treatments along with some fiber coating and packaging. Different adhesives can improve or decrease the sensibility and, more importantly, can change their behavior in large temperature ranges. In order to make FBGs suitable for temperature measures, it is strictly required to decouple thermal contribution on wavelength shifts from those generated by other factors. The test campaign described in the following sections aimed to experimentally verify the K_T value (when FBG are exposed to thermal cycles in vacuum) and to assure a bonding strategy able to make negligible mechanical strain on the sensors.

II. EXPERIMENTAL SETUP

The overall data detection system includes several elements. In the following list their main characteristics are reported.

Figure 2. The SmartScan interrogator employed

- **Optical fiber and FBG**. The fibers were all placed and fixed on a Kapton layer to thermically calibrate the FBGs. To sustain the extreme temperatures and avoid the problem of outgassing, fibers with a polyimide coating were used with a bare fiber sensor. During the tests, performances of 28 FBGs were analyzed.
- **FBG interrogator**. It is the device that can independently acquire data from FBGs by sending a laser beam through the fibers, collecting the sensors' outputs and sending them to the host PC. It is wavelength based and can, therefore, have multiples FBGs on each of its four channels if they have different wavelengths. Once per minute the interrogator runs a data acquisition loop with a variable frequency between 2,5 and 25 kHz and use the instantaneous wavelength value is the average of all the data acquired.
- **Thermocouples**. They are electronic temperature sensors based on the Seebeck effect. They are made by two different conducting materials that are joined forming what is called a "hot junction". This junction will be the measuring part while the other two end are connected to the measuring machine. The magnitude of the voltage measured is directly proportional to the temperature. Thermocouples are used to calibrate and compare the results with the FBGs.
- **Thermo-vacuum chamber.** Where tests were conducted. The chamber can depressurize the environment down to values of 1*10-8 mbar, while working in temperature ranges between -190 °C and +160°C and the minimum temperature value is dictated by the use of nitrogen. Heating elements like heating IR lamps and cryocoolers can be used to extend the temperature ranges. All measurements were made at $1*10^{-8}$ mbar in a temperature range of -170°C to 220°C.

III. TEST CAMPAIGN

The test campaign is divided into three distinct phases and each one pursued a different sensor attachment methodology:

- Adhesive disposed directly on the FBG;
- Adhesive fixed near the FBG but not over the sensor;
- without adhesive.

The results are thus compared for trying to define the most effective fixing technique. Clearly, each step improved the subsequence once with the results gained.

A. Test 1: adhesive on the FBG

In the first test a silicone adhesive (qualified for space environment) was used to bond the fiber on the Kapton layer. Each sensor was further protected by a thin layer of Kapton tape. No tension was applied to the fiber before the process.

The thermal cycle applied in vacuum chamber can be divided into three steps:

1. Decrease to -170°C;
2. Rise to room temperature;
3. Rise to 220°C.

For each step a temperature holding was performed in order to reach the thermal equilibrium in the chamber, which has a long stabilization time due to vacuum.

An example of data collected is reported in Fig. 4. At first, it appears how correlation between wavelength ($\Delta\lambda$) and temperature (ΔT) shifts remained stable in the steps between environmental temperature and 220°C. However, as shown by the graph, random oscillations in the FBG output were detected when cryogenic temperatures were reached. Such steep steps are consistent with the hypothesis of mechanical slips caused by crystallization of the adhesive.

Although it remained in place for all the test, the contact area with the fiber was no longer homogeneous, so causing a random mechanical disturb on thermal data. Consequently, this not a priori predictable trend is incompatible with reliable, accurate and standard FBG calibrations for industrial applications. Moreover, a not completely linear trend is viewable for the FBGs calibration curve (Fig. 5).

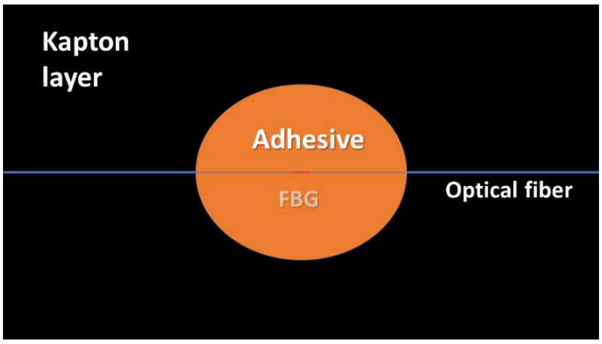

Figure 3. Scheme of bonding technique

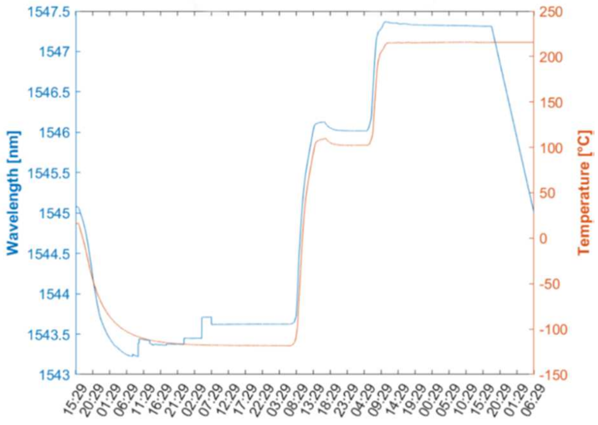

Figure 4. Data from FBG and Thermocouple during test 1.

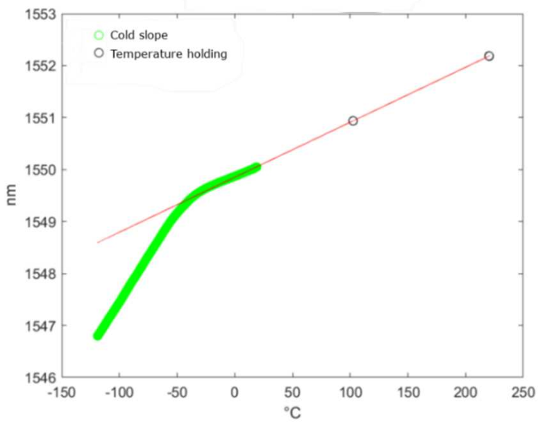

Fig. 5. FBG calibration curve in test 1.

The value of K_T changes significantly when the sensor is exposed to cryogenic temperatures: in particular, it occurs in a short thermal range at around -50°C. Above and below this transition phase (indicated as "*knee*"), two different linear trends are anyway the best fit of the experimental data.The coefficient K_T assumes an higher value below the knee, with a ratio between the two values of about 3.-Comparing results from different sensors, the values of K_T coming out from experimental data are similar among each FBG, even if it is possible to observe an uncertainty caused by the manual assembly of the set up. Finally, a faster response of FBG (compared to thermocouple) to thermal changes was registered. This first test showed how silicone adhesive applied directly over the sensor did not provide enough accurate measures, due to mechanical slips induced at cryogenic temperatures.

B. Test 2: adhesive near the FBG

In the second test the bonding technique was changed (Fig. 6) in order to prevent the random trends at cryogenic temperatures previously described. The adhesive's geometry was modified, thus avoiding the direct contact with the sensor. The same thermal cycle of the previous test was performed by the vacuum chamber.

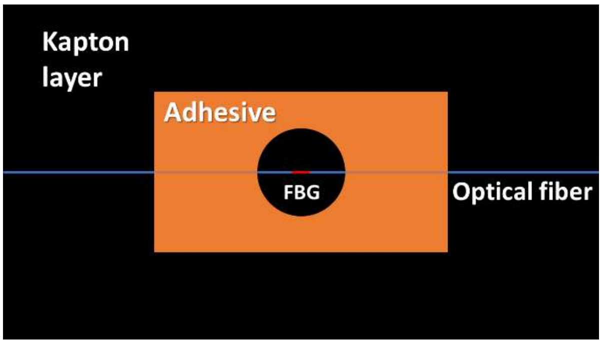

Fig. 6. Scheme of bonding technique in test 2.

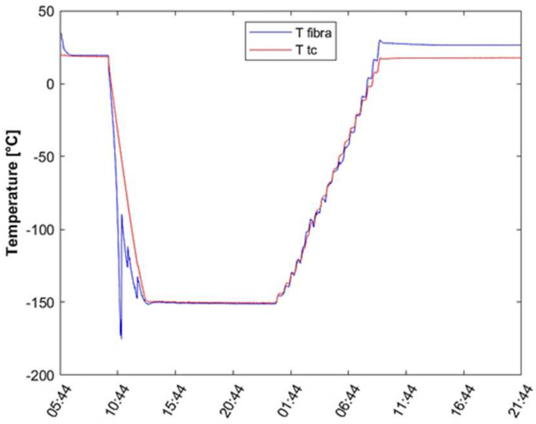

Fig. 7. FBG and thermocouple data in test 2.

However, as reported in Fig. 7, the results showed a great disturb generated by the mechanical slip. In fact, not only it did not disappear but even it increased in terms of oscillations amplitude, so making the thermal measures not reliable again.

However, after the first really high disturbed phase (at the end of the thermal decrease), data became really more stable and accurate. Moreover, considering the calibration curve, the transition phase at about -50 °C was observed again. Nevertheless, in this case the ratio between the two values of K_T was significantly lower. Furthermore, comparing the λ(T) calibration curve among all the sensors, a higher uncertainty about K_T definition was found.

To summaries, this configuration resulted even less reliable than the previous one.

C. Test 3: no adhesive

In the third test the bonding technique was radically changed (Fig. 8). Indeed, sensors were tested without silicone adhesive, which was only used to fix the fiber on the support really far from sensors. In this way, FBGs were held in place only by simple Kapton guides, realized with the same material of the support. The above-mentioned guide was thought in order to protect and avoid excessive displacement, but without possibility of generating possible mechanical disturbs.

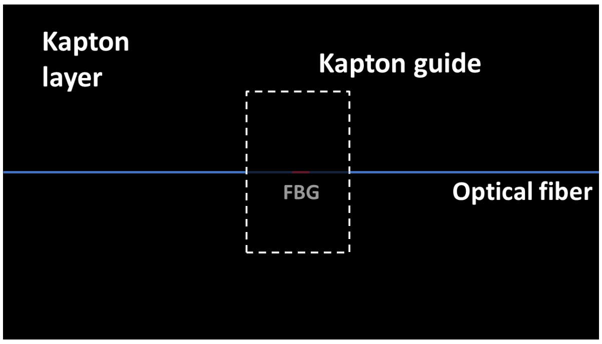

Figure 8. Scheme of bonding technique in test 3.

This time the results were really positive and encouraging. At first, any kind of mechanical disturb disappeared. The behavior is the same for all sensors, showing more homogeneity and stability than the previous tests. The calibration curve radically changed, becoming really similar to those reported in literature [19], [20].

More in details, over the knee the K_T maintained a value similar to that of previous tests. Instead, for lower temperature (between -50 and -170 °C) it significantly decreased: consequently, the ratio between the two linear fits moved from about 3 (first test) to about 0,5. Furthermore, the uncertainty introduced by the manual set-up (in terms of K_T dispersion by comparing all the sensors) radically diminished too. Obviously, the greater homogeneity of data allowed to obtain a more accurate correlation between FBG measures and temperature.

It is important to compare the precision of the measurements of FBGs with the thermocouples. It is required to have a tolerance range of ±0,1°C to be able to substitute thermocouples. This requirement is satisfied as reported in Fig. 11.

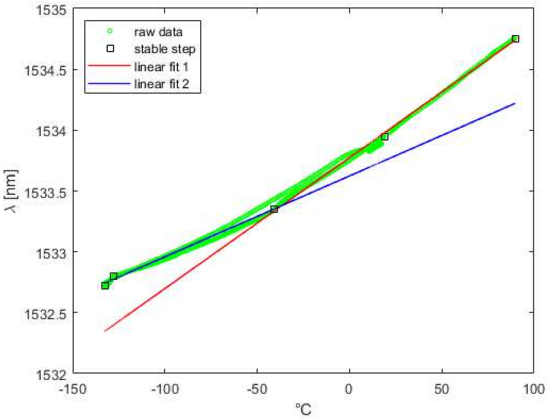

Figure 9. FBG final calibration curve

Figure 10. Comparison between Temperature measures by FBG and thermocouple

Figure 11. Comparison between the precision of FBGs and thermocouples

IV. CONCLUSIONS

Several sensors coated with polyimide as temperature sensors were tested in a thermo-vacuum chamber at 1×10^{-8} mbar in a range of temperatures between -170 and 220 °C. Three different configurations were explored:

- Adhesive disposed directly on the FBG;
- Adhesive fixed near the FBG but not over the sensor;
- without adhesive.

Criticalities were found at low temperatures when the adhesive was present. Although space-qualified silicone adhesive was used, the combination of vacuum and cryogenic temperatures generated some mechanical slips that interfered with wavelength readings.

Instead, the results of the sensors not fixed with adhesive showed a temperature sensing and data stability comparable to thermocouples. Moreover, FBG showed a fastest response to temperature changes. All the system has a overall low encumbrance compared to the conventional system with thermocouples. All the extra weight generated not by the thermocouples but the electrical cable harnesses can be avoided. This configuration gave encouraging results for the application of FBGs in space.

The positive results suggest to explore new adhesives and packaging techniques to improve resistance and precision. Thermal curing cycles are being investigated to have more homogeneous results and eliminate all internal stresses. Further studies are required to determine their behavior in a larger temperature range and under irradiation to qualify them for space application. Finally, a standard bonding technique is required for moving from laboratory test into industrial applications.

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