A GENERAL APPROACH FOR REAL-TIME RAIL CONDITION MONITORING USING OPTICAL FIBER SENSORS

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Railways defects such as broken rail endangers the safety of railway operations. In order to ensure the railway safety and a secured travel we present a method for monitoring railways. Our purpose is to obtain a proof of concept, monitoring system for the rail that can be trusty, accurate and has the potential to be used remotely. In this work an extensive sets of experiments has been performed in order to analyze the possibility of using optical fiber sensors for monitoring railways. The investigations refers to the behavior of optical fiber sensors response to temperature and strain changes in order to evaluate railway expansion.

Keywords: fiber Bragg grating, distributing sensing, railway track, temperature changes

1. Introduction

Maintaining over ground and underground rail networks poses significant economical, engineering and logistics challenges due to the complexity of structures that are part of the networks and because of the necessity to assure increasing transport capacity, increasing trains, metro and trams speed, decreasing environmental impact and a high level of security [1,6,7,9]. This days, two main categories of techniques are currently used for damage identification and for monitoring the railway tracks. One is based on visual inspections - the primary technique used for defect identification in the tracks structure. This is a robust method but the successful implementation of this method generally requires accessibility for physical inspection, many specialized workers and depends on the weather condition. To summarize, this method can be costly, time consuming and ineffective for large and complex rail systems. Another one is by applying non-destructive testing technologies such as ultrasonic inspection or the usage of fiber optic sensors of any kind. Ultrasonic Inspections represents common usage in the rail industry in many countries [2, 3].

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Optical fiber sensors (OFS) are more attractive since they offer multiple advantages because of their compact size, light weight, electrical isolation, multiplexing capabilities, multi-parameter sensing capacities and because they show high performances regarding their sensitivity. OFS make use of optical fibers for transmission and sensing environment. An example of an optical fiber (OF) based sensor is a fiber Bragg grating (FBG) which is used for investigating temperature and strain changes. We can use FBG to measure local physical parameters such as temperature or/and strain, knowing precisely, after interrogation, where is the short section of the fiber exposed. The FBG acts as a wavelength selectable mirror achieved by creating inside of the fiber a periodic modulation of the refractive index inside the core of an OS [1].

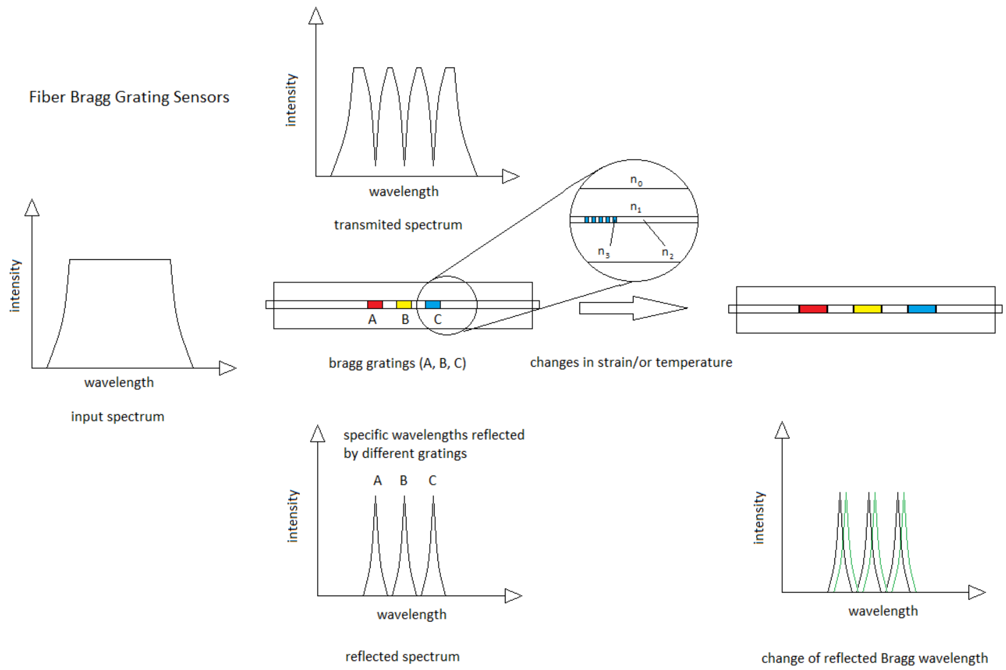

Fig. 1. Functioning principle of three multiplexed FBGs

If a broad number of wavelengths strike such a grating (Fig. 1) then a specific wavelength is reflected back along the fiber whilst the majority of wavelengths continue to propagate unperturbed [1]. The condition to be reflected is that its wavelength equals Bragg resonance wavelength, λ_B, in the other cases being transmitted [4]. Since the period of the grating is sensitive to the local changes of strain and/or temperature, the reflected Bragg wavelength is influenced by the gratings period [1]. The equation that describes how a FBG operates is given by:

$$\lambda_B = 2n\Lambda \qquad (1)$$

This shows the relationship between the reflected Bragg wavelength, λ_B, the effective refractive index of the core of the optical fiber, n and the period of the grating, Λ. Local strain and/or temperature differences may produce change to the period of the grating which results in a Bragg wavelength shift. [1]

As the safety is one of the most important aspects of the rail operations this research has been conducted in order to create a system for detecting broken tracks since it is associated with the safety of critical infrastructure [2, 8], and any undetected defect could cause train derailments with potentially catastrophic consequences for public safety, the economy and the environment [3]. Since weather conditions exert a major influence on railroads and one of the parameter which prove to be very important is temperature because it produces uneven thermal expansion or contraction of track that can lead to the buckling of the railroads or the crack of the rails we decide to apply different optical fiber sensor systems to a similar sample with the same chemical composition in order to study their behavior [5, 10].

The remainder of this paper is structured as follows: section 2 – experimental setup and tests run inside the laboratory, section 3 – discussion on the results and remarks while in section 4 we present the conclusion of this work.

2. Measurement setups

Our first set of experiments focused on characterizing several sensors regarding their sensitivity with temperature changes. A "Memmert UE 300" temperature chamber was used. Three sensors were displaced separately, inside the temperature chamber and the fourth one was applied by spot welding to our metal piece (dimension L x l x h: 30 cm x 7 cm x 0.5 cm). The fourth sensor has some particularities since its design includes two FBG fibers, one of them used for temperature compensation.

Actually the fourth sensor, commercial type (Micron Optics – Optical Strain Gage os3155), was used in order to find out if there is any kind of strain induced in the sample because of temperature change thus demonstrating again the influence of the weather parameters (temperature) to rail.

These experiments involve the manipulation the fiber, decide on the experimental setup, make the necessary online connections with the hardware and special equipment used for measurements, cleaning connectors according to the standard recommended usage.

In the first set of experiments we used a SM 125 Optical Interrogator from Micron Optics. The built-in platform responds directly to the user commands of the optical interrogator core which permit full spectral scanning and data acquisition, providing measurements with high accuracy, flexible software processing, and high dynamic range performance. Settings, sensor detection, data visualization, storage can be run on an external PC. The equipment provides full spectrum measurements in real time making it a good candidate for continuous long-term health monitoring of complex structures.

In the second sets of experiments we applied a single mode optical fiber to the metal sample using standard epoxy and again exposed it to heating cycles inside the temperature chamber using this time for analyzing an optical backscatter reflectometer “OBR 4600” designed by Luna Inc. in order to analyze the strain / temperature effects with distributing sensing by observing the relative changes of the refractive index inside the fiber fixed to the sample.

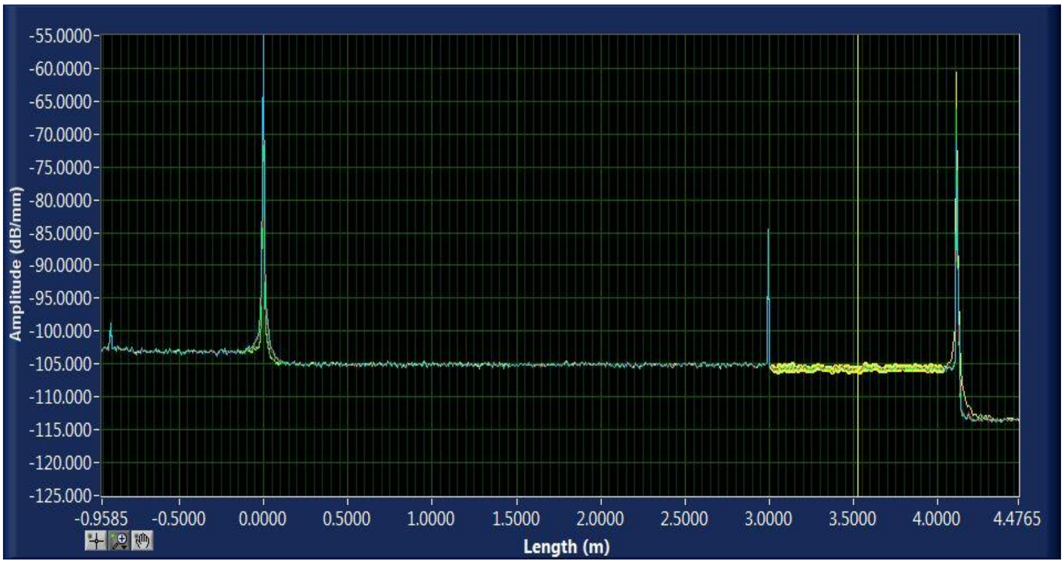

Fig. 2. Set up as investigated with Luna OBR 4600 optical backscatter reflectometer

Our setup, consists of: a) connection fiber (with a length of about 3 m.), which can be easily identified in the fig. 2 (starting from 0 ending at 3 m.) b) fiber under test, fixed to the element , that has a length of about 1.1 m (from 3 to 4.1 m in fig.2.)

LUNA OBR 4600 offers testing capabilities with high measurement speeds and a 0.02 nm spectral resolution. This equipment has the ability to measure distributed temperature and strain profiles along an optical fiber up to 70m with high spatial resolution and provides a good way to identify and locate macro-bends, splices, connectors and breaks.

3. Experimental results and remarks

The results obtained in our first sets of experiments are shown in the next figures (Fig. 3 – Fig. 6).

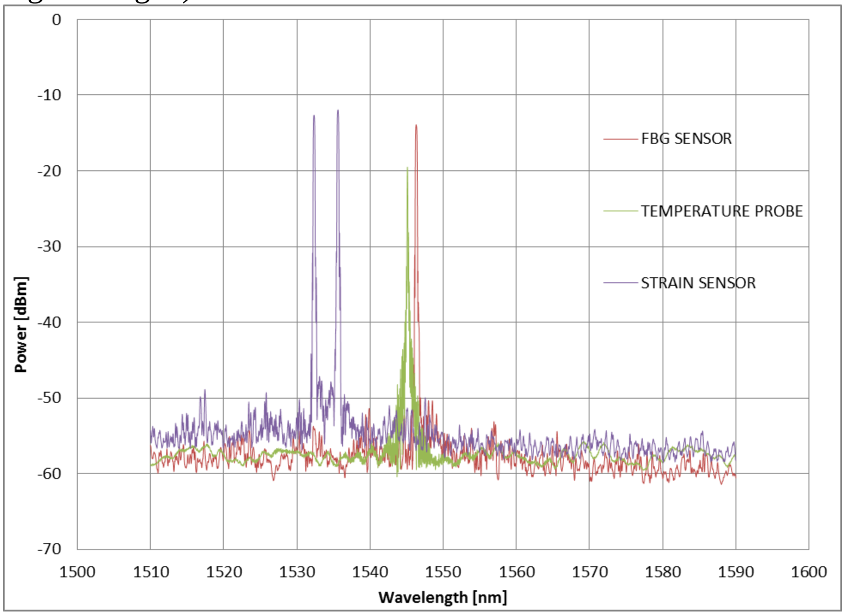

Fig. 3. Full spectra of four OFS used in the setup: Strain gage consisting of two FBGs for temperature compensation, one temperature probe and one standard commercial FBG

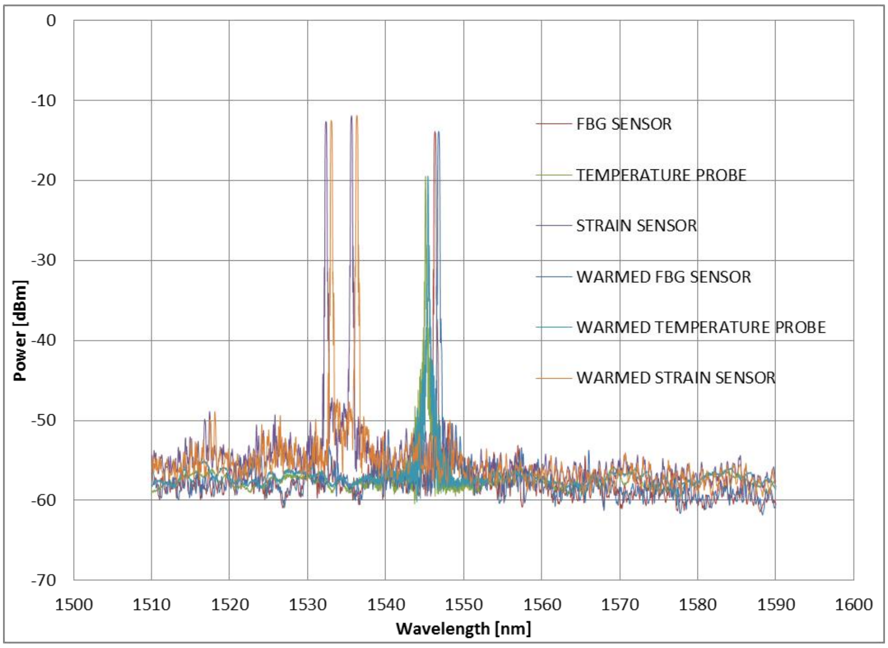

Fig. 4. Full spectra of the OFS before and after controlled heating.

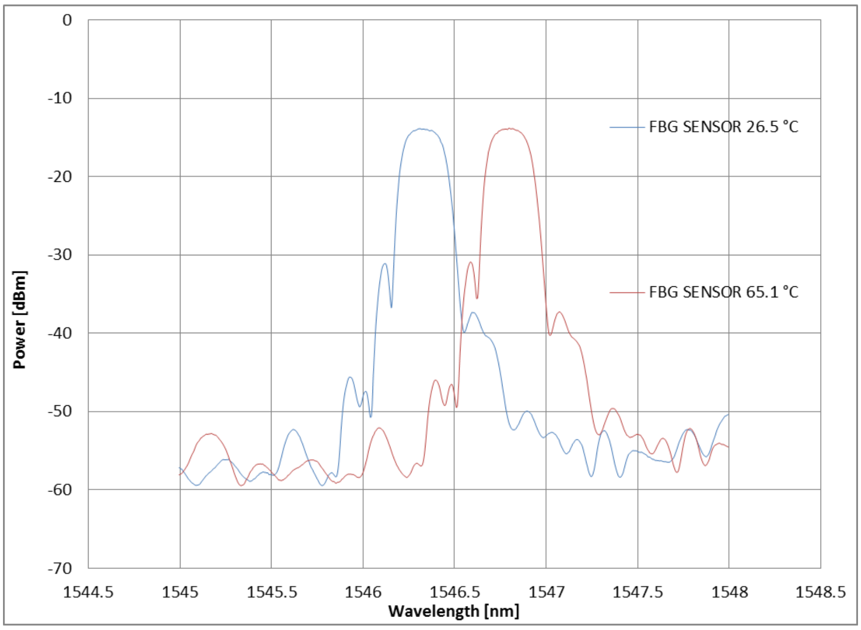

Fig. 5. Changes in the spectral profile of the OFS induced by heating

Fig. 5 shows us how easily we can provide data visualization in a specific zone. Of course during our experiments we were able to observe in real time the changes that appear over the entire spectrum and even to take a closer look to a specific spectral zone.

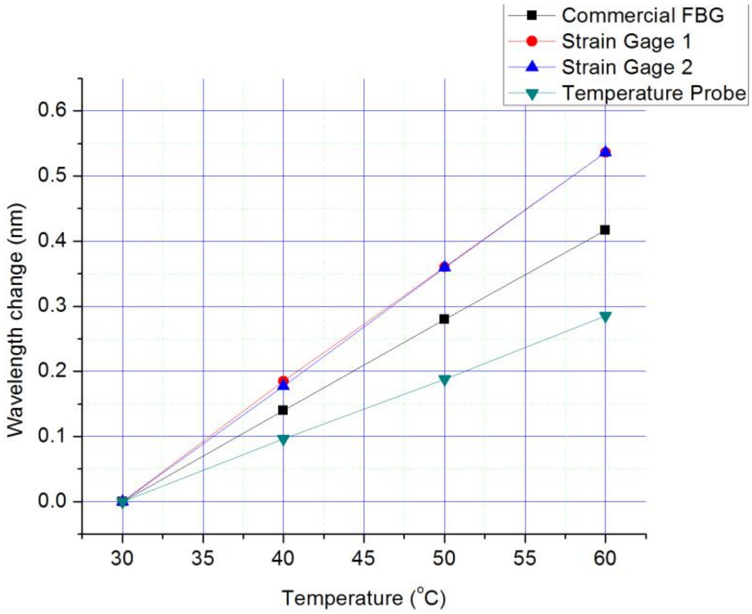

Fig. 6. Relative wavelength change of the OFS while subjecting the sample to heating up to 60 ºC

The accordance between the change of the wavelength and the temperature is shown in fig. 6

No major difference was noticed in the behavior of the FBGs from the strain gage when subjected the setup to a temperature difference around 30^{o}C. Since the point of the experiment is to prove and analyze changes due to strain and separate the temperature / strain effects, we focused on a different approach. Distributed sensing can prove to be more efficient in this range of temperatures. While FBGs are discreet, using the optical backscatter reflectometer gives the opportunity to have an overview over the whole sample under test therefore we can better notice possible degradation due to expansion of the sample.

The initial results did not point to significant change in the Bragg sensors due to temperature changes.

The second setup gave us the results explained below. What happens with the fiber, and also with the bonded area of the fiber, can be easily noticed in the figure 7. We mention that the fiber is fixed on the entire length of the metal sample (L=30 cm) and can be identified in the fig. 7 (starting from 3.4 m).

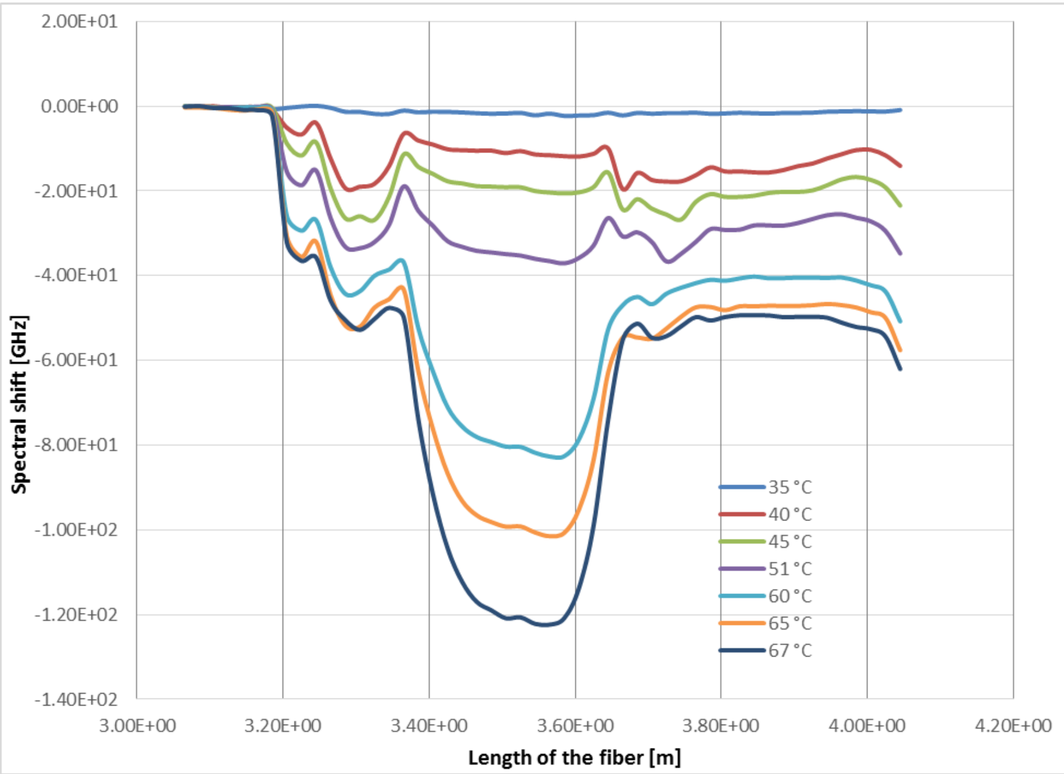

Fig. 7. Spectral shift, for the entire fiber, due to temperature change.

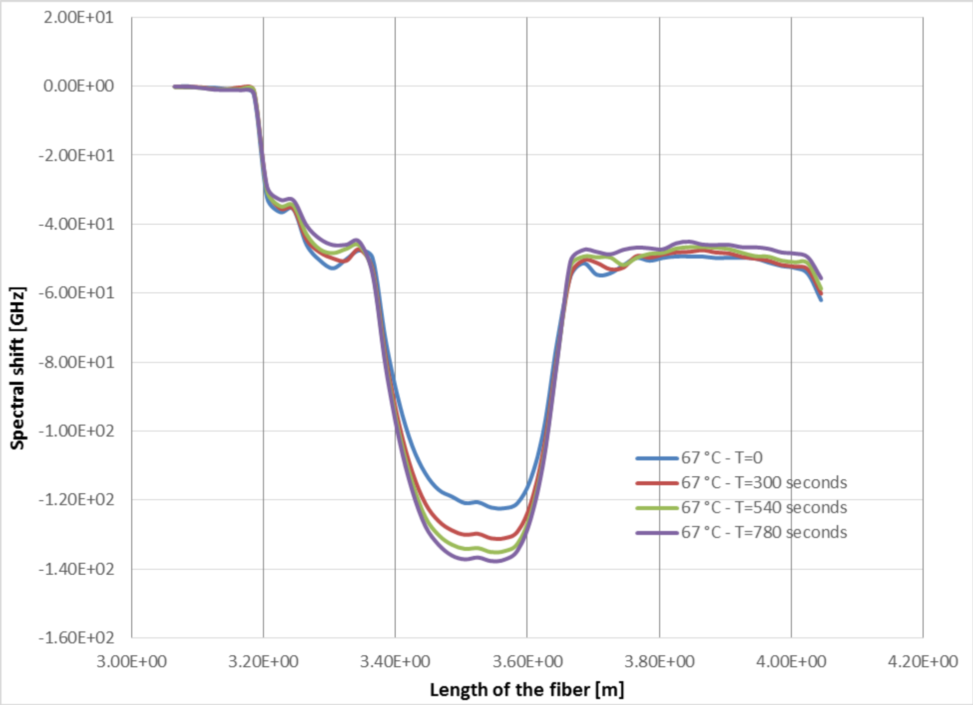

Fig. 8. Spectral shift change, for the fiber due to expansion of the sample.

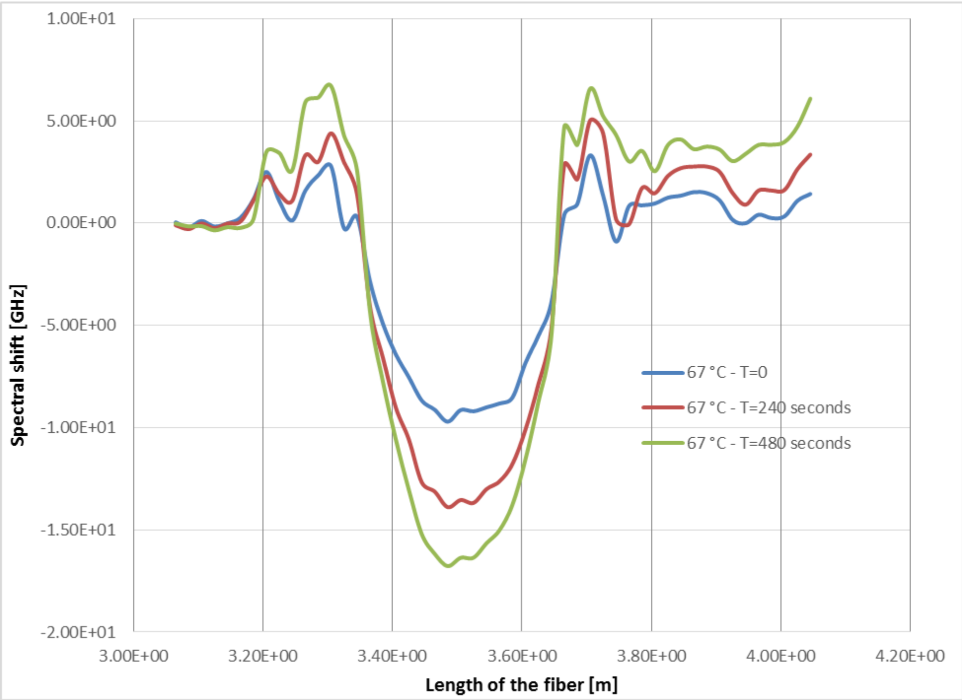

Fig. 9. Real time monitoring of the sample with respect to the expansion due to higher temperature

After reaching 67 °C the temperature chamber stops heating and with distributing sensors we can see that the fiber starts cooling in the unbonded area. Still, in the bonded area, we can notice changes in the spectrum due to expansion of the sample. As the effect over the refractive index change is similar to an increase of temperature the process is more complex and also involves the expansion of the material, aditional stress because of the applied epoxi witch is also subject to temperature change inducing aditional effects over the fiber (fig. 8).

Another representation of the same phenomenon, now considering the spectral shift having the corresponding reference (for temperature of 67 °C), as the origin of the vertical axis, shows us even more clearly the change of the spectra without aditional heating (fig. 9). As part of the fiber clearly cools down, strain induced effect given by the expansion of the sample is presented as a result of the investigation, between 3.4 m and 3.6 m in figure 9.

After opening the heating chamber at room temperature, the temperature inside decreases and this can be noticed on the entire length of the fiber (fig. 10).

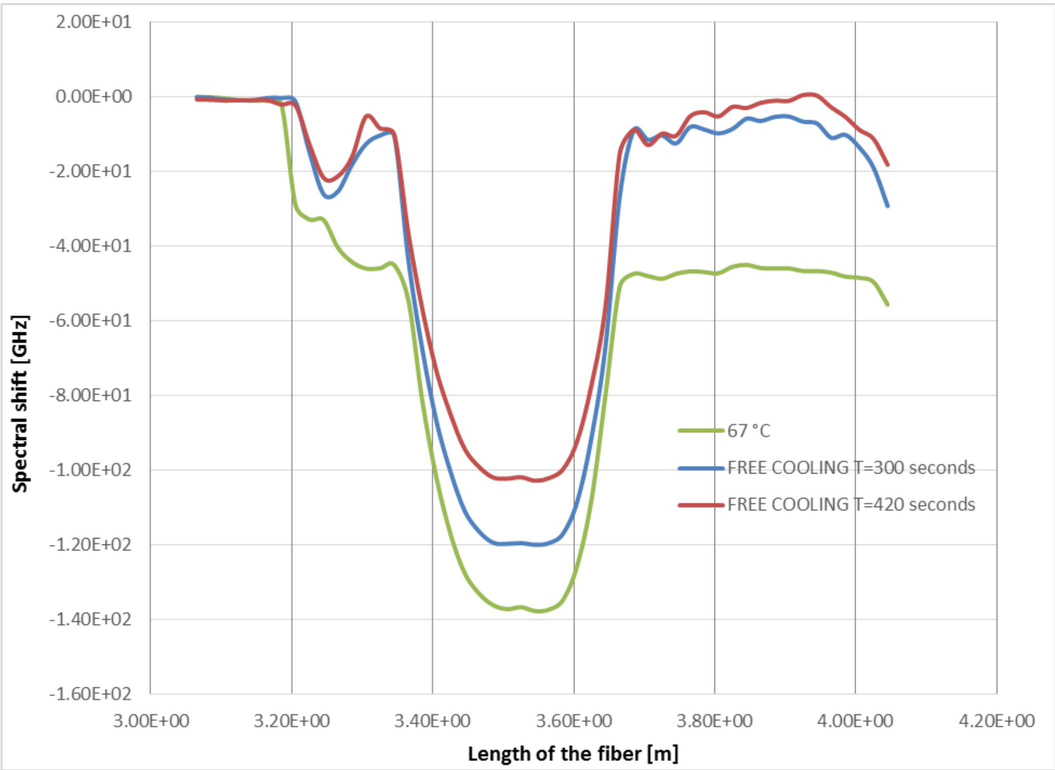

Fig. 10. Distributed sensing response while cooling the sample

In this case, we were able to notice spectral shift change on the entire fiber induced by cooling. However, the response of the sensor in the bonded area is determined by many factors including temperature and thermal expansion. This offers us the possibility to attach to rail or rail sub-components in order to observe the dynamic phenomena.

We believe that this preliminary results indicate that the sensors may be good candidates for calculating the expansion of rail components, but further investigations are required in order to assess a predictive maintenance system.

4. Conclusions

Since many rail systems has already the optical fiber communications infrastructure build, especially in urban areas, there can be a possibility for adopting optical fiber sensors for structural health monitoring of railways. This would allow building a remote monitoring system based on optical fiber sensors with low costs and minimal infrastructure changes. Due to many advantages over classical electrical sensors: small size and weight, electrical isolation, environmental resistance, and ability to be multiplexed, the fiber optics sensors can be used to monitor many important railway sub-systems. This permits real-time monitoring of the entire rail network in distributed points along the track.

In this particular paper, basic operating principles of distributing sensors and FBG are taken into consideration when studding temperature effect over expansion of a metal probe tested (with properties similar to the rail) which was exposed to the change of one of the principal physical parameter - temperature. The results show that there even if expansion was not able to be determined in the laboratory with the use of standard FBG based strain gages or temperature probes, using distributing sensing by fixing a standard single mode silica optical fiber on the same probe, can be efficient in detection of rail track expansion when simulating meteorological conditions in real life.

The results gained from this study also mark the possible problems that can occur when investigating strain induced effects over the tracks in real life. Of high importance are the different positions of the sensors when applied in the rail to the type of epoxy that is to be used. This could be of high importance when defining further works and seeking for improvements on stability, safeness and low maintenance costs of a detection system for defects induced in the railways. While some uncertainties remain, we do believe that we can create a reasonable and affordable system to predict/prevent rails cracks. Next steps taken into consideration would be to apply the fiber to the rail and to monitor inside a tram depot with and without traffic. Measurements are to be repeated for different weather conditions to check the stability over time. The key of this types of experiments is to separate the strain induced effects over the transport lines, by the pressure induced by the vehicles weight, the expansion due to heating and the direct response of the sensors with ambient temperature changes over day-night cycles.

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