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Temperature Compensation of FBG Sensors via Sensor Packaging Approach for Harsh Environmental Applications

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Highlights

- This paper focuses on temperature compensation on fiber Bragg grating sensors.
- Sensor packaging approach is considered in this study.
- A sensor package that can operate even in harsh environmental conditions is designed.

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Abstract

Fiber Bragg Gratings (FBGs) are one of the most preferred high technology sensors in the sensor market. Although, FBG based strain sensors are widely used they are most likely to get affected by climate changes such as temperature. Thereby, most of the time they have to be used along with a reference temperature sensor. Otherwise, one should be ensuring that the FBG sensor is isolated from the climate changes which requires more effort and is a less reliable approach as compared to using an additional temperature sensor. In this study, a novel design of temperature compensated FBG sensor package, manufacturing of polyimide coated FBG sensors, and finally montaging of the manufactured FBG sensors to the corresponding package with an appropriate adhesive is presented. In addition, the designed package has been tested under discrete and continuous loading conditions. Obtained results showed that with the designed package it is possible to measure the strain change in terms of sensing capability of 1.2 microstrains (με) up to 80°C with an extensive compensation ratio.

1. INTRODUCTION

Along with the rapid development in UV inscribing technology, the development of in-fiber gratings is also accelerated [1,2]. In this context, Fiber Bragg Gratings (FBG) is one of the most studied grating types in optical fiber grating areas due to their unique properties such as immunity to electromagnetic and radio frequency interferences, compatibility with composite materials, extremely light weights, and small sizes [3]. Although fiber Bragg gratings are manufactured using various methods, UV inscription of the optical fiber core is most studied in the literature. In this method, a collimated UV light beam is sent over a phasing material (e.g. phase mask). Light passes through the phase mask then guided through the optical fiber core and where the grating occurs as illustrated in Figure 1 below.

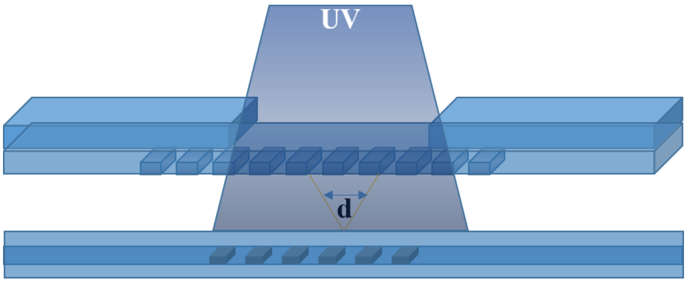

Figure 1. *FBG writing with UV inscription method*

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As the UV inscription method is less time-consuming and relatively lower cost approach as compared to other methods researchers have been conducted various studies to further improve the outcomes. In this manner, Hydrogen loading to the optical fiber approach had been an option that has been proven to induce grating growth. By this approach, researchers in [4] were eligible to increase the grating reflectivity with less excitation period and hence reduce physical deformation on the optical fiber. Moreover, some recent researches and applications focus on growing gratings in suspended-core photonic microcells with UV inscription [5]. By this novel method corresponding researchers made gratings resistive to even extreme temperatures and aided to reduce complexity in Type-II FBG sensor manufacturing approaches.

Although, many studies conducted for highly durable FBG sensor manufacturing methods, temperature compensation is another important research topic to be considered to use FBG sensors in harsh environment applications. In this context, researchers in [6] proposed a method in which tapered 2-array FBG structures in a capillary tube were used. By considering capillary tubes in fiber excitation researchers could significantly change the posing area to have an ultra-long grating length with a minimized intersection. As an outcome, strain sensitivity on a particular grating spot had been greatly increased. Besides, by tracking the Bragg wavelength shift on strain relieved temperature sensing FBG sensor researchers could establish a useful compensation approach. Moreover, in [7-9] researchers focus on placing the strain sensors under a certain tension while relieving the so-called temperature sensor to measure environment temperature [7-9]. By this method temperature effect on strain sensing FBG had been monitored individually and temperature compensation succeed.

On the other hand, researchers in [10,11] focused on a more complicated method in which 3rd order four-wave mixing (FWM) is used for sensitivity increment by comparing the optical powers observed in first and second FBG sensors. As a result of this study, a relation between strain and temperature effect on optical power was discussed and compensation succeed. On the other hand, relatively less time-consuming methods had also been applied for temperature compensation. For instance, in [12] researchers designed a package structure in which the strain sensor was glued through the direction of force, while the temperature sensor was placed perpendicular to the force direction and hence the effect of strain on the second sensor was minimized. So that, the second sensor was only measuring the temperature which is then used as a reference sensor for proper temperature compensation.

As a result of literature research, it was seen that considering the usage of various types of coating materials can also provide novel approaches for temperature compensation. In this context, the researcher in [13,14] used a 2-FBG array in a unique optical fiber in which the first FBG is coated with ORMOCER material whilst, the second FBG is left uncoated (bare). By that, researchers aimed to monitor a greater wavelength shift due to moisture-carrying particles sticks on ORMOCER and measure a combination of moisture and temperature. On the other hand, strain relieved bare FBG measures temperature only and allows for temperature compensation.

Eventually, a number of the approaches for temperature compensation drastically increases along with the sharp development of technology with the FBG array packing approach that is discussed in this study, temperature compensation had been assured to be over 95% in an instant and slow temperature changes. Moreover, it was also proved that temperature changes with a sensitivity of 0.1 ^{O}C and strain change up to 13000 $\mu\varepsilon$ with a sensitivity of 1.2pm/ $\mu\varepsilon$ can be achieved with the FBG sensor packing approach.

2. MATERIAL METHOD

2.1. FBG Sensor Design Principles

Any changes in temperature or strain in FBG structure cause wavelength shift as they are physically causing changes in the grating period. Thereby, to properly indicate strain effect on gratings individually temperature impact has to be compensated. In this context, the concentration of this study is to design a temperature compensated strain sensing FBG package that will aid to isolate strain impact on gratings from the environmental conditions.

For the uniform FBGs, gratings are lined horizontally with a particular period (ʌ) which is already assigned while designing the phase mask. This value of period is directly proportional to the central wavelength with the formula shown below in Equation (1) as given in [15]

$$\lambda_B = 2neff \,.\, \Lambda \,. \tag{1}$$

As it can be seen from the formula given above grating wavelength (or central wavelength) is equal to the multiplication of effective refractive index (n_{eff}) and grating period. The effective refractive index of the optical fiber is a constant that is directly related to the type of optical fiber used. While the grating period is a variable that depends on the phase mask pitch. In this context, any physical effects on the grating region directly cause a shift in the grating (central) wavelength. This relation can be numerically expressed as given below [16]

$$1/\, \lambda b \,.\, \partial\lambda b/\partial\xi = 1/n \,.\partial n/\partial\xi + 1/L.\, \partial L/\partial\xi \,. \tag{2}$$

That is expressed in Equation (2), any physical changes on optical fiber (expressed with (ξ) symbol in Equation (2) causes a shift on central wavelengths. To properly distinguish the impact of environmental changes individually Equation (2) should be modified respectively. By that, the amount of shift in central wavelength to strain shall be analyzed with the following equation [17]

$$\Delta\lambda b/\lambda b = (1/n\ dn/dL + 1/L)\ \Delta L = (1 - pe)\ \varepsilon z \,. \tag{3}$$

Photoelastic effect (p_e) shown in Equation (3) value is a constant parameter and equals 0.78 for the polyimide coated optical fiber as calculated with Equation (4) shown below [17,18]

$$pe = n2\ /2\ \{p12 - \nu\ (p11+p12)\}= 0.22 \,. \tag{4}$$

When the value of the photoelastic constant is substituted into Equation (3), the relation between strain and wavelength shift can be obtained as in [19,20];

$$\Delta\lambda b/\lambda b = 0.78\ \varepsilon z \,. \tag{5}$$

Finally, the relation between the Bragg wavelength shift and strain can be summarized as in Equation (6) which is also given in [20,21]

$$\Delta\lambda b \approx 1.2\ pm/\mu\varepsilon \,. \tag{6}$$

Besides the strain change impact on gratings, the effect of temperature change should be considered as well as in Equation (7)

$$\Delta\lambda b/\lambda b = (1 - pe)\ \varepsilon z + (\ \alpha+\eta)\Delta T \,. \tag{7}$$

In Equation (7) α represents the thermal expansion coefficient and that is accepted to be 0.55×10^{-6} / °C for the Coherent R1550B-P polyimide coated fiber which is the fiber type used in this study. Besides, it is also known that the thermo-optical coefficient (η) Equals to $8.6x\ 10^{-6}$ / °C. By substituting these two coefficients into Equation (7), one can get the temperature sensitivity of the polyimide-coated FBG sensors as 10.2 pm/°C in generic form.

Eventually, to achieve previously explained goals for proper temperature compensation process of manufacturing is to be followed as stated in Figure 2 below.

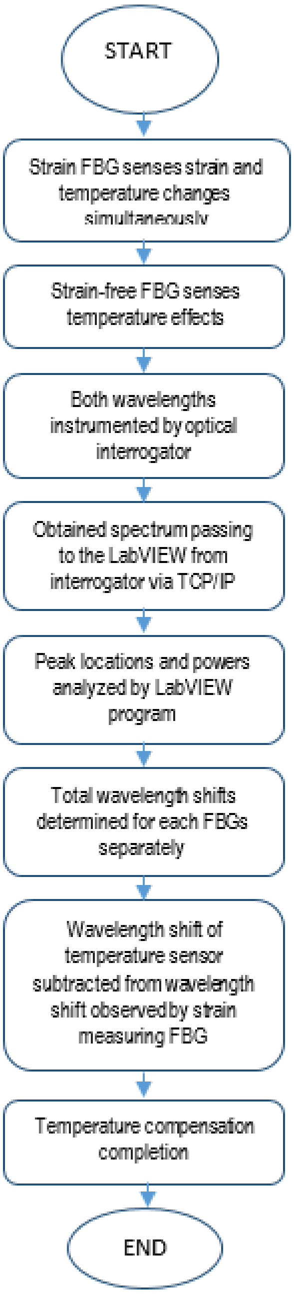

Figure 2. *Flow chart of proposed package working method*

2.2. Temperature Compensated FBG Sensor Package Design

Package design is one of the most important steps in temperature compensation operation as it has a direct impact on grating sensitivity, accuracy, and repeatability. Hence, in this part of the study few key points were considered and explained in detail. The first of those considerations is the manufacturability of the designed package. As the package needed to be sensitively manufactured a proper material and method had to be chosen. At this point, particular researches on the field show that SS304 stainless steel is one of the best options with its great availability and handling opportunities. Thereby, during package design, SS304 material was considered. Besides, another key point is the physical distance between two FBG sensors which affects the package size.

As it is previously experienced, for an effective temperature compensation FBG sensors in an array must be positioned as close as possible to each other [20]. On the other hand, the spectral distance of the two

FBG sensors in the array must be greater than 4nm to prevent cross-talk and overlap situations. By considering these key points, an individual FBG sensor package was designed that allows ones to position two FBG sensors overlaid in the same optical fiber with 30mm physical distance as illustrated in Figure 3.

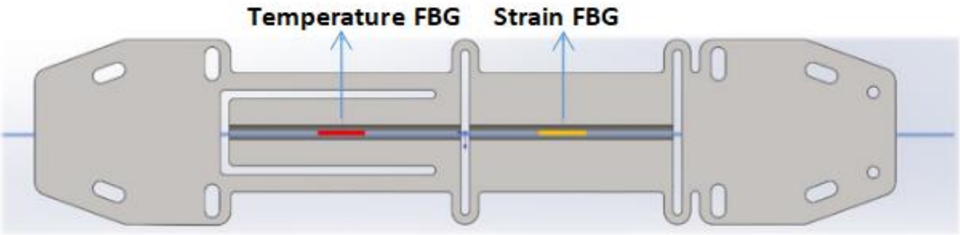

Figure 3. *Back view of the designed package*

In the above-shown package design temperature sensing point was designed to be strain relief towards horizontal force. By that, it's aimed to achieve an accurate temperature sensing point that will not get affected by the strain changes. Besides that, two sides of the strain sensing points were also freed with laser machining to assign two sides of the strain sensor as the weak region. So that, sensitivity of the strain sensor will be amplified. Moreover, both heads of individual points were also freed with laser machining as shown in Figure 4 below, to allow one-two montage package on the corresponding surface via welding or epoxy approaches. Lastly, there were two holes prepared to squeeze the protective jacket of the pigtail using an additional metal cap and so that provide an additional anchoring point.

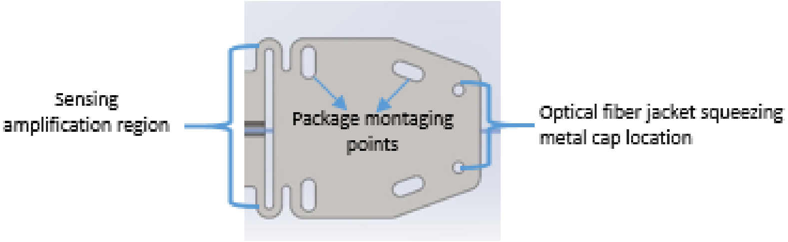

Figure 4. *Proposed montaging holes and fiber anchoring point*

At this point, it is worth mentioning that optical fiber jacket squeezing material was manufactured by a 3D titanium printer. The main reason for this approach is that after a while FBG sensor metal packages are welded onto the surface, oxidation may occur at joints and loosen the optical fiber. Therefore, to prevent this problem, a titanium-64 material metal cap was printed as shown in Figure 5.

Figure 5. *Optical fiber jacket tightening cap manufactured by 3D printer*

2.3. Tensile Test and Manufacturing of The Proposed Package Using ANSYS

Theoretical tests are known as valuable guidance of practical tests. Thereby, to theoretically define the maximum force that the proposed package can stand and ensure the strain transfer constant differences on strain sensing spot and temperature sensing spot on the package a tension test was completed using ANSYS software and obtained result shown in Figure 6.

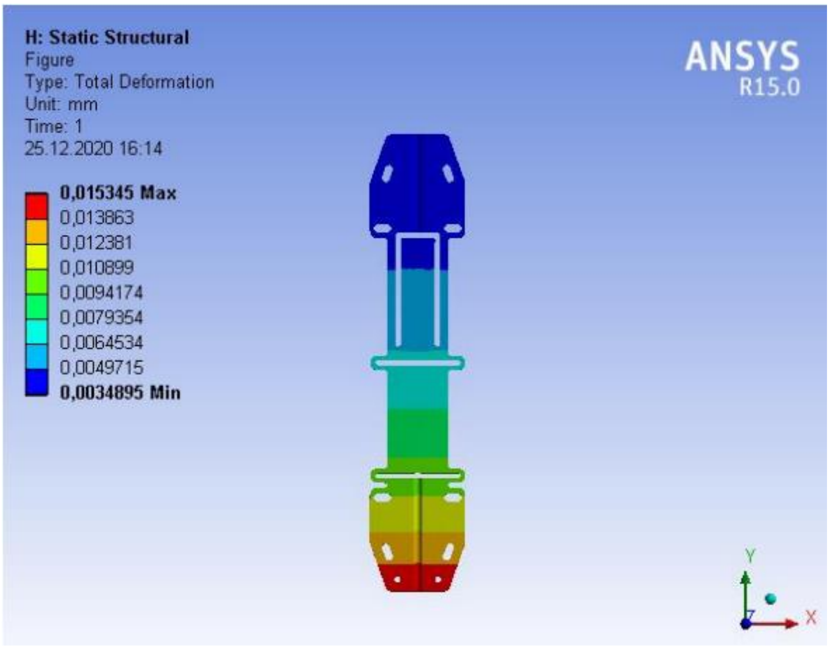

Figure 6. *The outcome of the proposed package tensile test using ANSYS*

The test was carried out in two steps, at the first step fixed point was assigned to be the package head close to the temperature sensor and at the second step, a vice versa approach was considered. Obtained results showed that the proposed package was capable of surviving up to 3000N. Besides, in both scenarios, there was a strain transfer coefficient difference between a strain and temperature measuring spots in which the temperature level was always lower as compared to the strain measuring point. By that, a proposed package was considered to be manufactured. At this point, for its sensitive manufacturing options, fiber laser was used and the package was manufactured as shown in Figures 7 and 8 respectively.

Figure 7. *Front view of proposed package*

Figure 8. *Back view of proposed package*

2.4. Manufacturing of Two-FBG Array and Montaging to the Package

As previously mentioned, for fabrication of the temperature compensated FBG package structure polyimide coated Coherent SMF-28 type photosensitive fiber was chosen. At first, central wavelengths of the FBG arrays were assigned such that they are 30nm spectrally distanced from each other. The reason for choosing two wavelengths 30nm spectral distance is that capacity of the package was uncertain. Hence, to prevent overlap, FBG sensors had to be spectrally located far away from each other. The FBG manufacturing process was handled using the UV inscription method. In this study, an Exci Star excimer laser was used which has 193nm wavelength, 250Hz repetition rate, and 5mJ pulse energy. As a result, an FBG sensor array of two FBGs were obtained that have reflectivity over %50. Designed FBG sensors with the length of 5mm each had side lobe suppression ratio (SLSR) greater than 12dB and full width at half maximum (FWHM) value 250pm. Mechanically stripped and UV inscribed FBG sensors then recoated with PI2525 polyimide using Vytran polyimide recoater. To ensure that strain sensitivity of the FBG sensors is still

1.2pm/με, the manufactured FBG array was then tested using NORTHLAB linear stage. This stage linearly applies a horizontal tension to the optical fiber with the force of 0.1N up to 7N with steps of 0.1N. The obtained outcome showed that FBG sensors were kept at the same sensitivity level during the manufacturing process. By that, at the next step FBG sensor array was montaged to the packaged structure as shown in Figures 9 and 10.

Figure 9. *FBG sensor array montaged to the package (back view)*

After montaging the FBG sensor array to the packaged structure, tightening caps were also placed to tighten the protecting jacket shown orange in the color above.

Figure 10. *FBG sensor array montaged to the package with tightening caps*

3. EXPERIMENT AND ANALYSIS

In this study, a setup was prepared as shown in Figure 11. This setup consists of a temperature-compensated FBG sensor array, an optical interrogator which operates at 1500nm-1580nm with 5kHz of sampling rate, one optical isolator for FBG reflection measuring, and a developed LabVIEW program.

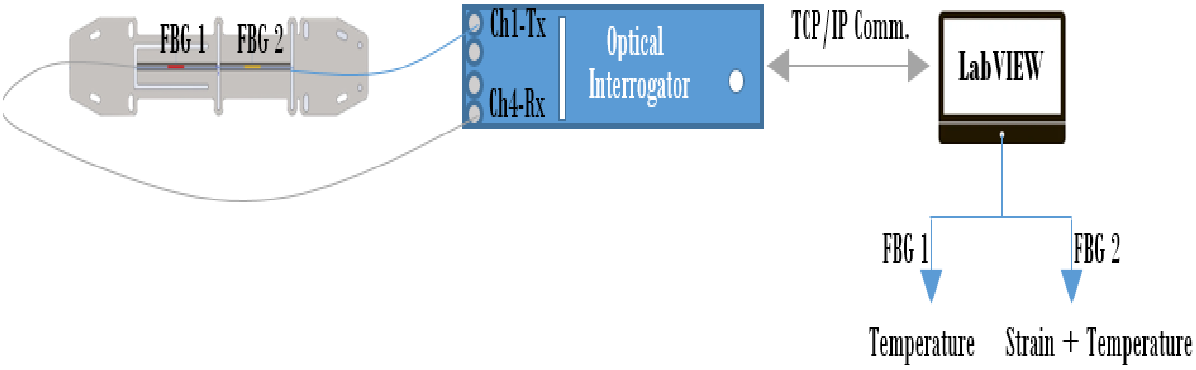

Figure 11. *Entire system setup*

In the experiment, the Micron Optics SI255 interrogator transmits light through channel 1. Broadband light passing through FBG 2 and FBG 1 then goes into an optical isolator which basically blocks transmitted light and only allows for wavelengths reflected from each FBG sensor. By that, a transmission deep is observed which is consecutively used for reflection calculation. Although sensing calculations are made using reflected wavelength, it is important to monitor transmitted light deep to identify instant power drops.

3.1. Temperature Sensitivity Analysis

To ensure the capability of temperature compensation of the proposed package temperature sensitivity had been analyzed. Hence, a manufactured package consisting of two FBG structures overlaid on the same optical fiber was tested under certain conditions. As temperature impact on the grating structure is an important topic to be studied an industrial type cleanroom oven (shown in Figure 12) was used which guarantees uniform heat distribution all over the chamber.

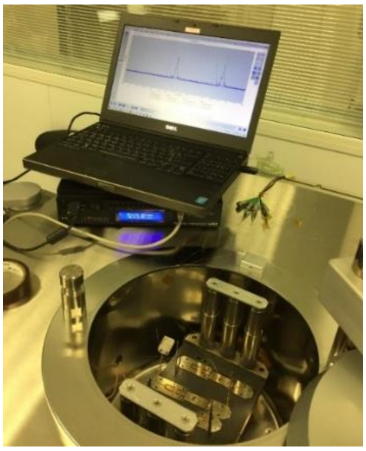

Figure 12. *Temperature testing of proposed FBG sensor package*

To ensure the repeatability of the proposed package sensitivity, the test was conducted using ideally manufactured three FBG sensor packages and Bragg wavelengths tracked simultaneously using MicronOptics SI255 optical interrogator. In the mentioned test, starting temperature was assigned as 20℃ and the final temperature point was assigned as to be 70℃. Moreover, the temperature rise time per degree Celsius was decided to be 25 seconds. Hence, the test was completed in 21 minutes. Eventually, obtained results showed that temperature and strain sensors responded evenly while oven temperature rising and decreasing respectively.

After ensuring temperature and strain sensors responded evenly to the temperature change next, the sensitivity of the temperature sensor in the proposed package was determined using the MATLAB curve fitting tool. By substituting the data saved during the test into CFT of MATLAB a correlation curve was drawn. As a result of correlation approach, few outcomes were achieved. Those are respectively; temperature sensor responded linearly to the temperature change and 0.09 nm of total shift occurred concerning 50 °C temperature change as shown in Figure 13. Hence, the temperature sensitivity of the temperature and strain sensors respectively calculated as 1.8 pm / ℃.

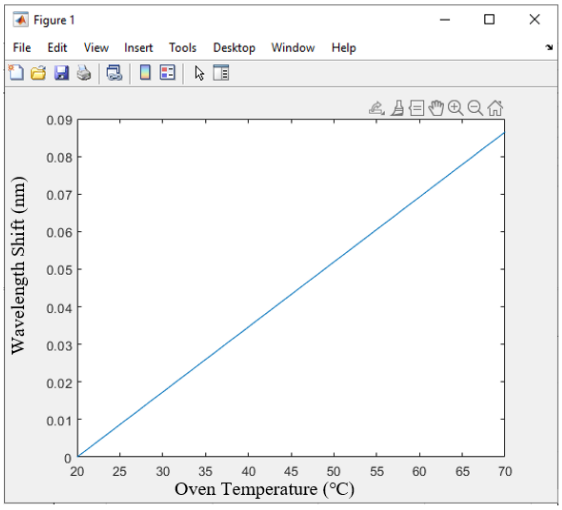

Figure 13. *Wavelength shift vs oven temperature graph*

As previously mentioned, nominal temperature sensitivity seen at unpackaged FBG sensors was 10.2pm/℃, while in this study temperature sensitivity was obtained as 1.8pm/℃. The reason for this sensitivity difference is due to the temperature sensor being placed on the FBG sensor package under 4N tension and stainless steel housing material collecting the heat at weak points that are close to the gratings.

3.2. Tension Test of Temperature Compensated FBG Package

After completing the theoretical tension test and oven test of the proposed package, a tension test using Shimadzu AGS-X 250kN tensioning system was carried through. During the test, handed on 3 FBG packages were placed to the system and linear tension was applied continuously until the optical fiber is physically broken. In this stage of the test, tension speed was kept out of consideration. In the first place, it is very worth mentioning that, entire data acquisition is completely handled using a data acquisition program that was developed using the LabVIEW platform. The main reason for developing a unique software program for this study was to track minor changes in real-time and collect data for signal analysis. In this manner, data collected using the mentioned program was then processed and wavelength shifts of the individual sensors for the time graph were obtained as shown in Figure 14.

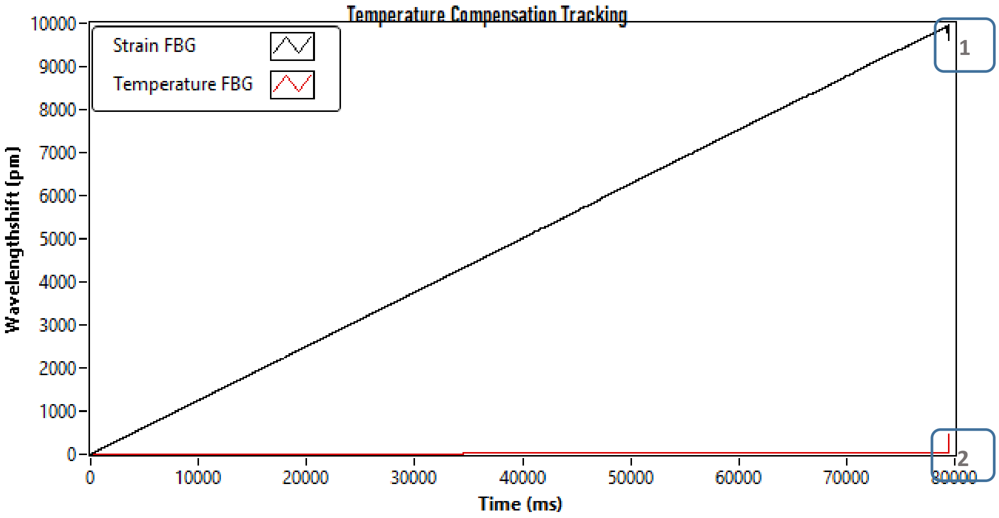

Figure 14. *Wavelength shift vs time result of first specimen*

Although the strain sensor in the FBG array was linearly responded up to 9930pm (refer to circle 1) wavelength shift, there were not any considerable reactions observed by the temperature sensor (refer to circle 1). Hence, it was seen that strain isolation of the temperature sensor has been properly done which enhances the reliability of the proposed package. Moreover, the tension test was repeated by considering another two specimens. Ideally manufactured the second specimen was also tested with the same approach as the first specimen. Obtained results showed that the second specimen could survive up to the 9380pm wavelength shift while the third specimen survived up to over 13000 pm wavelength shift.

To determine the impact of the speed of the tension on the grating structures, a tension test was repeated by getting tension speed into account as well. According to this approach, another set of FBG sensor packages that consist of three ideally manufactured FBG packages were tested under different stroke levels as 1mm/min, 0.1mm/min and 0.01mm/min respectively. As an outcome that was realized even though all the packages have likewise strain-stress curves, durability point decreases as stroke speed rises. To be more specific, when a certain tension is applied in terms of 1mm/min, the FBG package survived up to 4674pm wavelength shift while the same tension applied at 0.1mm/min and 0.01mm/min speeds, FBG packages survived up to 7585pm and 13033pm wavelength shift respectively. On the other hand, to calculate the sensitivity of the strain sensor in terms of micro strain (µƐ), the total wavelength shift concerning tension speed data sets was then manipulated using the curve fitting tool of MATLAB software. As an outcome, a correlation curve was obtained which consists of all the specimens and results shown in Figure 15 below.

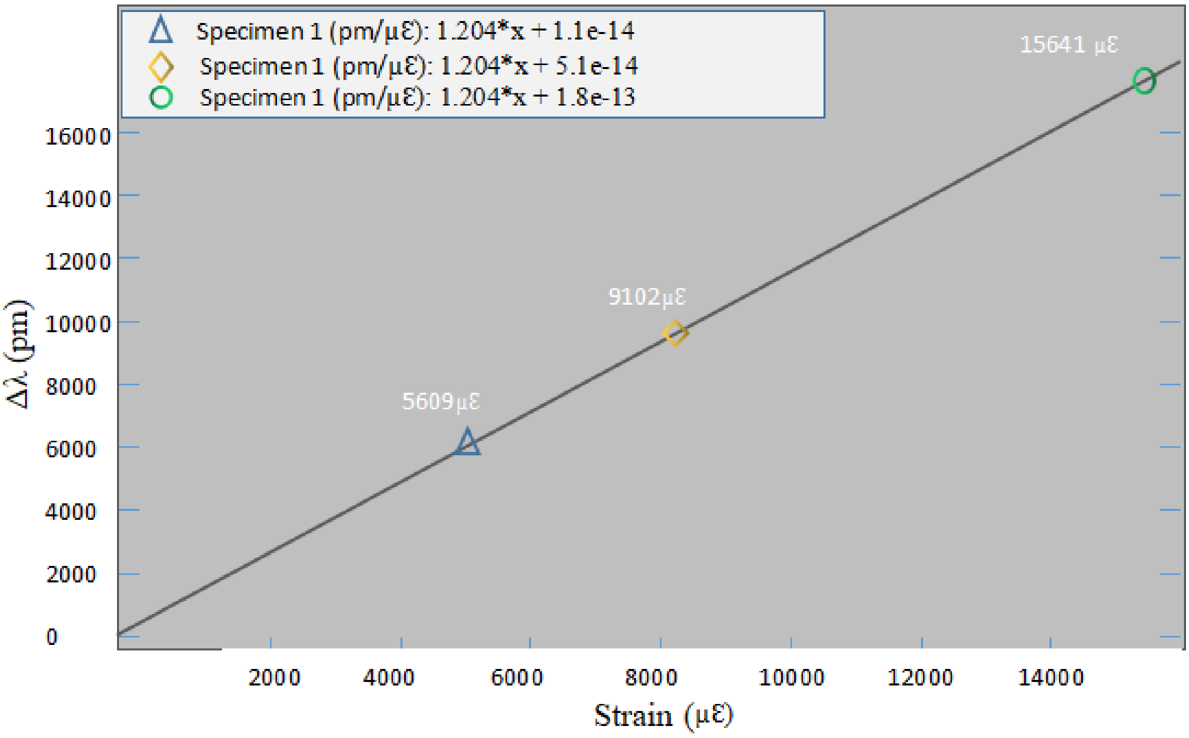

Figure 15. *Proposed packages sensitivity graph*

The above graph shows that uniformly manufactured temperature compensating FBG sensor packages have the sensitivity value of 1.2pm/µε. As previously mentioned, strain sensitivity of the bare fibers to wavelength shift is 1.2pm/µε under normal circumstances. Therefore, the proposed package can be used for strain measurement without facing any reductions in terms of sensitivity. On the other hand, as above shown test results explains, even the least durable temperature compensation package survived over 5600µƐ. Eventually, by this study, an FBG sensor package that compensates for the temperature impact over %95 and is durable for harsh environmental applications was successfully developed.

4. CONCLUSION

To compensate for the temperature effect on strain sensors even at high strain levels and instantly changing temperature conditions, a durable stainless steel FBG sensor package was designed, analyzed, and manufactured. Besides that, to first identify and then ensure the repeatability of the strain sensitivity of the proposed package, a series of tests were handled at different tension speeds. As it can be understood from the comparison table (Table 1) given below, obtained results showed that the proposed package is eligible to survive higher strain and temperature levels, without considering the instant changes at environmental conditions as compared to novel and previous designs. Eventually, a unique temperature FBG sensor package that can be used in any industrial and harsh applications had been manufactured.

On the other hand, results also showed that the strain capacity of the proposed package was not observed steady for each specimen. The main reason for this variation can be due to manufacturing and montage errors. To prevent this problem and precisely define a constant strain capacity manufacturing steps should be revised and the process should be handled with an automatic system in which manual operations do not take place. Eventually, a more industrial-like temperature compensating FBG package structure can be manufactured.

Table 1. *Comparison of the proposed package with recently developed sensors*

Reference Number	**Temperature Sensitivity**	**Strain Sensitivity**	**Max Strain**	**Operating Temp**	**Method**
[5]	12-16pm/ºC	-	-	100-1000 ºC	Furnace Tube
[9]	10pm / ºC	-	-	25-95 ºC	Combining FBG with (MZI)
[12]	19.29pm/ ºC	-	-	20-55 ºC	Strain-relief mounting FBG for temperature sensing
This study	1.8pm/℃	1.2 pm/ µƐ	>5600 µƐ	20-80 ºC	Temperature Compensation Package

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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