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FLEX-PATCH: A NOVEL, RUGGED, FIBER OPTIC STRAIN SENSOR FOR SHM APPLICATIONS

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Abstract

The design and development of a novel opto-mechanical strain sensor—called *FlexPatch* (patent pending)—based on the use of an optical fiber Bragg grating (FBG) mounted into a custom-made miniature metallic flexure is reported. The FBG sensing element is attached to a carrier flexure using proprietary bonding process which ensures a linear, drift-free and repeatable strain response even under severe moisture and temperature conditions. The sensor is uncompensated for temperature effects, but has undergone extensive mechanical and environmental testing and is qualified for use in a strain range of +/- 2,500με with a gage factor of 1.2pm/με over a temperature range from -40° to 120°C, and a fatigue life >$100x10^6$ cycles. The *FlexPatch* is intended for use in diverse sensing and monitoring applications, and can be installed onto surfaces by epoxy bonding or spot welding.

INTRODUCTION

Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications [1,2]. One of the most common applications is strain/stress sensing. A variety of discrete fiber strain sensors based on fiber Fabry-Perot cavities and fiber Bragg gratings, as well as distributed techniques based on Brillouin scattering methods, have been developed along with pertinent interrogation electronics and instruments [3]. However, one of the areas in need of further development and commercial maturity is sensor packaging and installation technique.

Real life commercial applications of fiber optic sensors demand that the devices operate effectively and reliably without any concern for faulty readings or degradation due to aging or weathering. As the commercial demands for fiber optic sensors grow, it is essential that new developed devices meet technical specifications sought by end-users as well as operating environments and conditions present in different application areas and industries were they will be ultimately installed and used. Hence, there is a need to: develop appropriate protective coatings and housings for fiber sensors; investigate the fundamental transfer of strains, stresses, pressure and temperature from the host specimen or matrix to the sensing fiber and the associated materials inter-play; as well as formulate field installation

processes and deployment techniques suitable for diverse applications and environmental conditions. This latter point is particularly critical for harsh environmental applications.

When it comes to the measurement of mechanical strains, electronic foil strain gauges have become *de facto* strain sensor of choice for the past 50 years for numerous types of applications. Nowadays, there is a large assortment of foil gauge types to meet the needs of any application or environment, along with an entire industry that provides all the necessary instrumentation, parts and ancillary components—such as adhesives, protective coatings, wire leads, etc. However, electronic gauges present performance limitations due to thermal errors, bridge balance, faulty mounting or wiring, difficult signal conditioning, and susceptibility to moisture and EMI interference.

Optical fiber sensors, in contrast, offer the possibility to perform strain and temperature measurements under harsh conditions in the presence of electrical noise, EMI interference and mechanical vibrations. Silica-based glass fibers are capable of operating up to 800°C, while sapphire fibers allow their operation at temperatures as high as 1500°C. Furthermore, given the wavelength encoded nature of FBGs and their intra-core fiber structure, they offer the capability to perform single- or multi-point, multi-parameter sensing with a single, continuous optical fiber. This simplifies tremendously sensor interrogation and multiplexing, reducing sensor installation time and costs. A single FBG array can, intrinsically, interrogate tens to hundreds of points with a single interrogating electronics and a main lead fiber cable.

However, all of these attributes are of no use if the devices are not robust and reliable, or cannot be effectively installed in the field and operate reliably under harsh environments. Therefore, what FBG-based sensors—and strain sensing ones in particular—have been missing, is a rugged protective packaging design that allows them to be handled without fear of damage and installed with the same ease and care as would be applied to conventional foil gauges. Offering such features will undoubtedly help accelerate the adoption of fiber optic sensors in the market and lead end-users to base their sensor selection—between conventional and fiber optic—on the basis of the overall performance and cost.

In this paper, we report the design and development of a novel packaged strain sensor based on the use of an FBG with a miniature opto-mechanical flexure, which we call *"FlexPatch"*. The package design offers both rugged environmental protection to the FBG sensing element, as well as ease of handling and installation. The packaged sensor size and footprint are comparable to those displayed by commercial foil gauges, and can be installed using standard adhesive surface bonding or spot welding techniques. Given its intrinsic features, reliability and cost, we expect that the *FlexPatch* FBG strain sensor will set the norm in fiber optic strain sensors and will become the *de facto* FBG strain sensor standard in years to come.
In the sections to follow, we describe in more detail the sensor's design and characteristics, as well as its packaging, fabrication and response—under static and dynamic strain, humidity, and temperature.

SENSOR PACKAGE DESIGN

A photograph of a fully assembled *FlexPatch* fiber strain sensor is illustrated in Fig. 2.1. The device is approximately 1 1/2" long by ¼" wide by 1/32" thick. The sensing element is an optical fiber with an inscribed FBG element. The fiber is mounted on a metallic carrier flexure which provides protection to the fiber during installation and in service.

The metal carrier in this design is selectively complaint in the axial direction—thanks to the use of open ring flexures at each end—while relatively stiff transversely, to make the FBG sensing element immune to transverse strain effects. As shown in Fig. 2.2, on the underside of the carrier, there is provided a continuous channel groove where the fiber sits. At each end of the carrier flexure, the fiber is secured in place using a proprietary bonding process resulting in a secure bond that does not slip or creep over time. The fiber is pre-tensioned—so that the device can operate both under tensile and compressive strains—with the FBG portion center in the middle of the carrier. The carrier consists of a stainless steel metal shim that is cut out from a large plate using a precision electron discharge machining (EDM), water jet cutting, or a similar process. This ensures that the carrier is not distorted and that no residual stresses are introduced, which might affect the sensor's strain response and repeatability.

As the carrier is stretched under the influence of the specimen's stresses, the FBG will also be stretched or compressed, resulting in a wavelength shift of its peak reflectivity. In this fashion, strain measurements are linearly correlated to the FBG spectral shift. The nominal strain sensitivity coefficient is then ~1.2pm/ με at 1550nm.

Figure 2.1. Photograph of fully assembled *FlexPatch* FBG strain sensor.

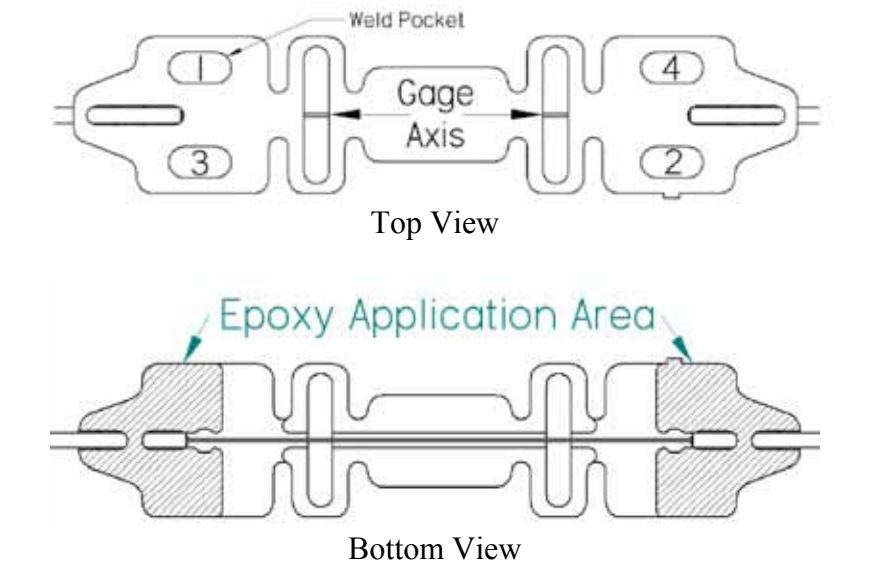

Figure 2.2. (Top) Top-view of the *FlexPatch* strain sensor; notice the four small wells used for spot welding onto a test specimen. (Bottom) Underside of the metallic carrier flexure. Notice channel groove where the optical fiber sits in.

The effective gage length of the sensor is defined by the distance between the anchoring or mounting regions of the carrier, which in this case are the four wells on the top-side of the carrier. These wells are used for spot welding the flexure to a solid test specimen and effectively define the anchoring points between which the FBG will be stretched or compressed as a function of the specimen's stresses. The flexure springs at either end, allow for axial movements of the carrier. Hence, this sensor construction allows the FBG to be rigidly attached to the test specimen at two opposite points, without constricting the fiber's movements within said points.

Because the FBG is free to move in between the anchoring points and the flexure's elasticity is much greater than that of the test specimen, the strain sensor's effective gage factor is primarily the intrinsic FBG sensitivity coefficient, which at 1550nm is roughly 1.2pm/με. However, the sensor displays temperature sensitivity, as conventional foil gages do as well, which is governed by the temperature sensitivity of the FBG, coupled with the mismatch in coefficients of thermal expansion (CTE) between fiber and test specimen. For the present design, an FBG temperature sensitivity of 9.77pm/°C was observed.

Figure 2.3 shows the strain response for the sensor once mounted to a steel bar specimen. It can be seen that the response is fully linear over a strain range of +/- 1,000με. In practice, strain ranges of +/- 5,000 με or more can be achieved, depending on carrier design, fiber pre-tensioning and FBG mechanical strength.

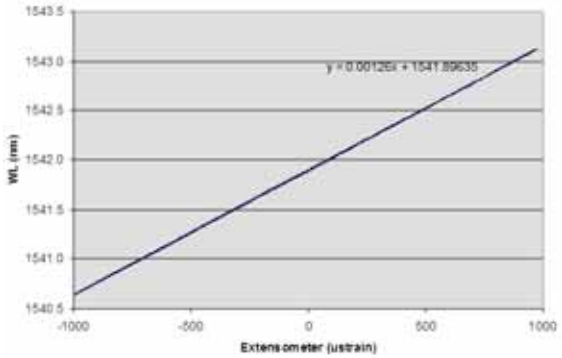

Figure 2.3. Strain response for a mounted *FlexPatch* FBG strain sensor on a steel bar

SENSOR FABRICATION

As shown in Fig. 3.1, the carrier flexure is batch fabricated from a steel metal shim plate onto which individual layouts of the flexures are carved out using EDM, water jet or etching techniques.

F**igure 3.1.** Metal shim sheet with an array of carriers pre-cut.

Individual pieces are removed, cleaned and inspected for further assembly. FBGs are then inserted into the carrier and secured in place using the procedure described above.

SENSOR TESTING

To validate the sensor's design and its robustness for real-life field applications, a batch of *FlexPatch* prototype sensors was fabricated and subjected to a mechanical and environmental qualification testing program consisting of static and dynamic strain testing, cyclic mechanic fatigue, high temperature soak and humidity accelerated aging.
All samples were mounted onto test steel bars using spot welding as shown in Fig. 4.1. Test bar designs and experiments were done according to ASTM standard E251guidelines.

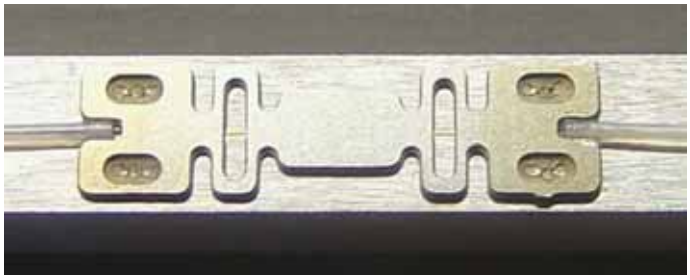

Figure 4.1. *FlexPatch* strain sensor mounted onto a test steel bar using spot welding.

Thermal Cycling Testing

Sensors were mounted on both sides of a steel beam and held under a constant strain of 1,600 με. The beam was placed inside a thermal chamber and the temperature cycled between -40° to +120°C for 500 cycles. All the sensors performed well with less than 5pm drift in the FBG's peak wavelength. Given the intrinsic temperature sensitivity of an FBG, it is to be expected that the FBG wavelength will shift under temperature changes even when held at constant strain. Fig. 4.2 depicts the temperature response of the *FlexPatch* under constant strain. It can be noticed that the temperature sensitivity in this case has increased due to the steel beam CTE, compared to that of the glass fiber for a net of ~27.4 pm/°C.

High-Temperature Soak

To determine the possible effects from prolonged high temperature exposure, such as fiber detachment, creep, drift, stress annealing, etc, mounted sensors held at a constant strain of 300 με were placed in an oven at 150°C. As shown in Fig. 4.3, no drift effects were observed, only a minor +/- 2 με deviation, for a period of 30 days.

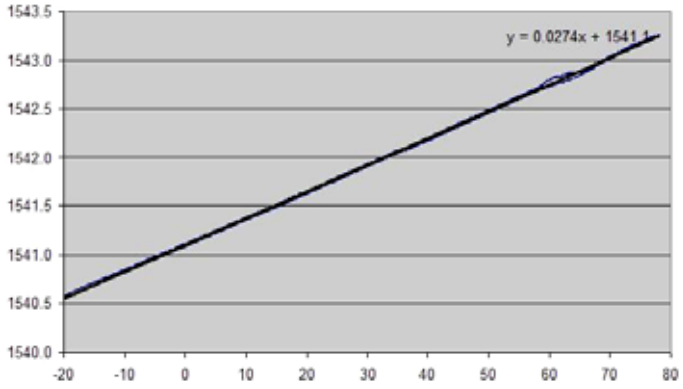

Figure 4.2. *FlexPatch* temperature response under constant strain.

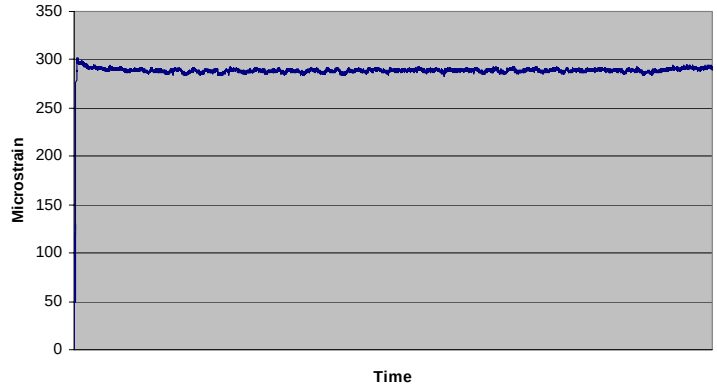

Figure 4.3. *FlexPatch* response under a 150°C oven soak.

Humidity Soak

In our previous strain sensor design work and testing [4] we observed that moisture ingression is one of the most detrimental environmental factors to affect fiber packaged sensors. A set of pre-mounted *FlexPatch* sensors were exposed to a 75°C/75% RH soak for a period of 1000 hours. A thermistor was used to monitor the temperature inside the chamber. As seen from Fig. 4.4, aside from the initial FBG shift due to the increase in temperature from ambient to 75°C, the sensor's response remained relatively stable under moisture exposure.

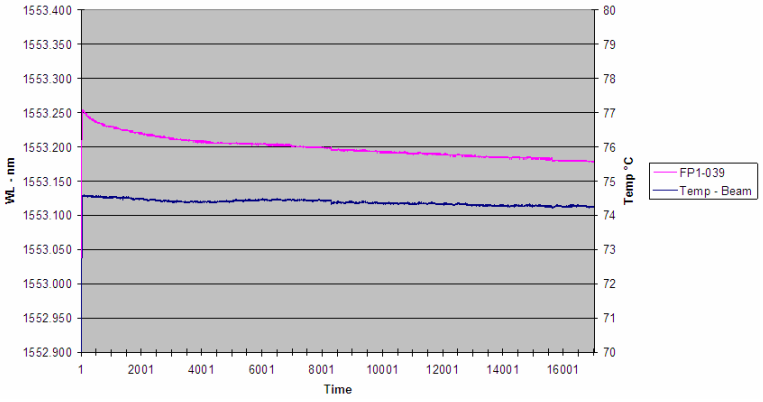

Figure 4.4. *FlexPatch* response under a 75°C/75% RH soak for 1000hrs.

To determine the variability from sensor-to-sensor to strain response, a set of 5 *FlexPatch* separate sensors were mounted onto the same constant stress test beam. Each strain sensor had an FBG operating at a different peak wavelength. The test beam was kept at constant stress and placed inside a thermal chamber. The temperature was cycled between -40° to +120°C to induce apparent strains. No variability among sensor outputs was seen (Fig. 4.5).

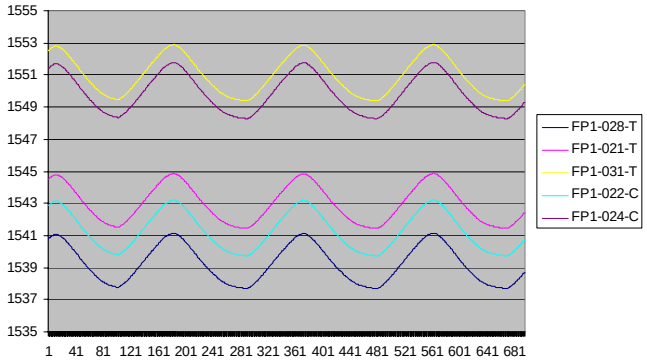

Figure 4.5. No variability response can be observed among different *FlexPatch* sensors under temperature cycling.

Mechanical Cycling and Fatigue

A critical aspect of any strain gage is its stability under continuous cycles of strain loading and un-loading and associated durability. To test for this, a *FlexPatch* sensor was mounted between two coplanar beams (see Fig. 4.6b), one fixed and the other driven on a mechanical cycling machine to provide a sine wave pattern for strain up to ±3,000 µstrain at a frequency of 20 Hz, as shown in Fig 4.6a. Several strain gages were tested from ±1,990 to ±2,950 µstrain. To monitor the temperature on the test beam (due to ambient room temperature changes and induced heating from the workload) a thermistor surface was mounted nearby the test sensor. As observed in Fig. 4.7, no degradation or sensor failures were observed on sensors tested over 100 million strain cycles. This number of cycles compares extremely well to those observed in commercial foil strain gauges at 1 to 10 million cycles.

a) **b)**

Figure 4.6. Fatigue test: a) Close up showing mounted *FlexPatch* sensors. b) Mechanical cyclic loading machine.

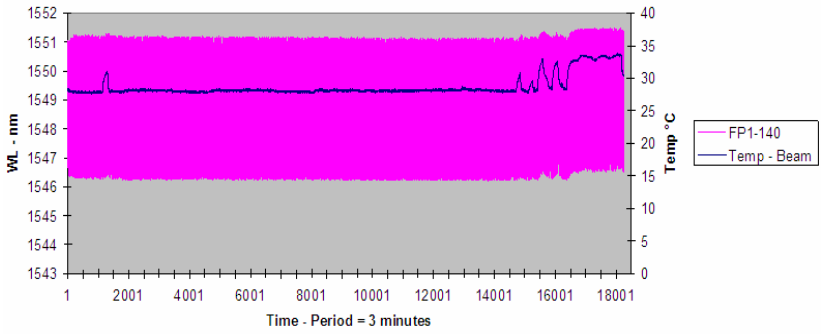

Figure 4.7. *FlexPatch* response over 14 million strain cycles.

CONCLUSIONS

A practical, rugged and novel miniature packaged FBG strain sensor has been developed. The sensor is based on the use of a metallic carrier flexure which protects the fiber and provides ease of handling and installation. Sensor installation and performance is similar to conventional foil gages, while its manufacturing process lends itself for batch fabrication of multiple devices at low cost with repeatable characteristics. Prototype devices were subjected to a rigorous mechanical and environmental testing, which qualified their use over an operating temperature range of -40° to +120°C (150°C under short duration), with a superb mechanical fatigue endurance $>2x10^6$ cycles and only minimal humidity effects. As designed sensors are capable of strain measurements over ± 2,500με with a gage factor of 1.2pm/με. Although the sensor is uncompensated for temperature in its present design, it only exhibits an apparent thermal strain of ~0.7με/°C.

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