Smart Sensing Polymeric Foil with Integrated Optic Fiber Sensors

Fabrication and characterization of a polymeric foil sensitive to strain.

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***Abstract*— A structural integrity monitoring system based on optic fiber sensors is an important development at the smart structures level. However, direct sensors incorporation, without a substrate structure, creates few difficulties in eventual sensor maintenance or replacement. This paper presents an approach to overcome this issue. The fabrication, using industrial fabrication processes, and characterization of a polymeric foil able to sense and gather sensitive information, and send it for remote analysis is explored. The described example uses Fiber Bragg Grating sensors embedded in laminated polymeric sheets commonly used in different industries, as automotive, aeronautic, civil, among others. The fabricated foil is capable of transferring the full deformation to the optical sensor. Tests indicate that the polymeric foil influence on the sensor performance may exist. However, the presented optical sensor incorporated in the polymeric foil is fully functional with high sensitivity, 0,6 picometer by microstrain, measuring deformation, up to 1,2 millimeter.**

Keywords- optical sensors; smart structures; fiber Bragg gratings, sensor integration

I. INTRODUCTION

Optical sensing technologies have several advantages that make them very attractive in a broad range of applications. Optical fiber sensors, in particular, provide low-cost solutions in the overall system, with immunity to electromagnetic interference, multiplexing capabilities and a high degree of miniaturization and integration. Nowadays, optical fiber sensors offer a high performance alternative, in comparison to standard technologies, in many different areas, either to measure physical parameters like strain, temperature or pressure, or to perform highly sensitive biochemical analysis [1, 2].

However, the incorporation of such sensors creates some difficulties in eventual sensor maintenance or replacement. Alternatively, it is proposed in this paper to incorporate optoelectronic instrumentation in standard polymeric foils that can be already found in different products, e.g., automotive and air craft floors and wall coverings. The advantages come from the easy applicability of foils in the monitored structure, allowing also the easy access for replacement. Moreover, integrated optical devices are now emerging as the next generation of sensing structures, where virtually any parameter can be determined with high accuracy in a highly miniaturized optoelectronic device [3].

Linking textiles or textiles-polymer-laminates with optical devices and electronics is becoming more realistic than ever. An emerging new field of research that combines the strengths and capabilities of electronics, optics and polymers like PolyVinyl Chloride (PVC) is opening new opportunities.

Industries, like the automotive, aeronautics, civil and biomedical are looking for solutions to gather information from their systems status. Lower production costs, wider exploitation of integrated circuit technology and wider applicability of sensor networks allows the integration of microsensors in almost any structure, providing the desired system data.

A. Fiber Bragg Grating Sensors

Fiber Bragg Gratings (FBG) are periodic changes in the refraction index of the fiber core made by adequately exposing the fiber to intense UV light. The gratings produced typically have lengths of the order of 10 mm [4]. When an optical beam is injected into the fiber containing the grating, the wavelength spectrum corresponding to the grating pitch will be reflected, while the remaining wavelengths will pass through the grating undisturbed, as exemplified in Figure 1 [5, 6]. Since the grating period structure is sensitive to strain and temperature, these two parameters are measured by the analysis of the reflected light spectrum. This is typically done using a tunable laser containing a wavelength filter (such as a Fabry–Perot cavity) or a spectrometer [4].

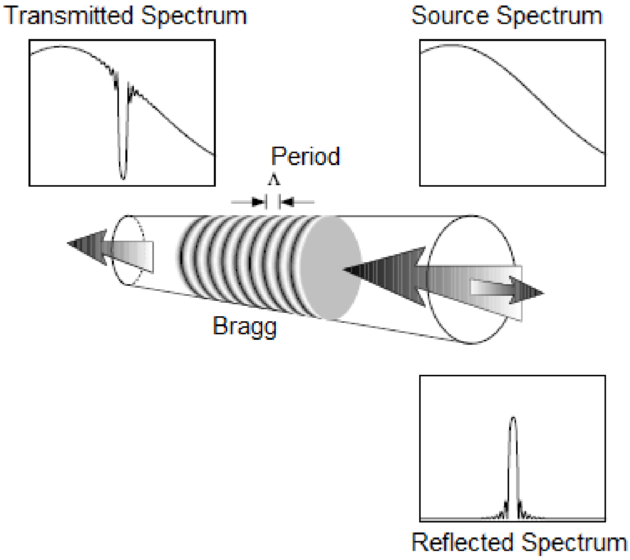

Figure 1 - Illustration of a Bragg sensor principle.

A resolution in the range of 1 µε (micro-strain) and 0.1 ºC can be achieved with the best demodulators [4]. Since we are dealing with optical sensors that are sensitive to temperature and, in this case, also to strain by the same manner, a few issues may appear when measuring both parameters simultaneously. In this case, it is necessary to use a strain free reference grating that measures the temperature alone, in order to compensate the temperature error from the sensor network and measure the correct strain values.

A main advantage to use Bragg gratings is their multiplexing potential [5]. Many gratings can be written in the same fiber at different locations and tuned to interfere at different wavelengths. This leads to the possibility for measuring strain at different locations along a single fiber. However, since the gratings have to share the spectrum of the light, there is a trade-off between the number of gratings and the dynamic range of the measurements on each of them.

B. 1.2. Polymeric Foil

Plastisols are liquid dispersions of a divided thermoplastic resin, generally PVC, in a plasticizer. These resulting pastes are highly viscous mixtures that become solid on heating. When cooled, the plastisol provides a tough material with good physical characteristics and with a service temperature range of 0°C to 125°C [7]. The plastisols commercial success is mainly due to the low cost and easy applicability. Long-term flexibility is the main advantage, which means that the plastisol supports relative motion between host substrates. The plastisol material can be formulated to comprise specific characteristics. It can be a soft foam or a dense hard solid material, resistant to chemical attack, self-extinguishing or to provide good weatherability [7].

The major drawback is the cure temperatures that may be too high, limiting their use on specific substrates or applications.

II. FABRICATION

The optic fiber used in the model fabrication was a single mode Corning 28e, a standard fiber for communication applications with acrylate coating. The Bragg structures printed in the core of the fiber were in the communication wavelength range (1520-1570 nm).

The fiber optic sensor is packaged within a sandwiched polymeric foil (Figure 2). The integration of the fiber in the foil is a crucial step since there may be some loss of sensor sensitivity by the foil.

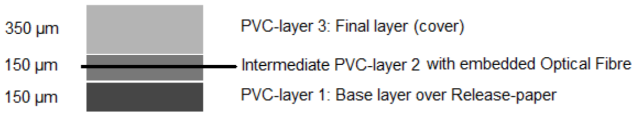

Figure 2 – Sandwich approach.

The fabrication relies on an industrial process (Figure 3). A first layer is applied in a structure that will work as substrate for the fabrication process. After the thickness homogenization, the layer is cured in the oven and become a solid structure. The second layer suffers only a partial cure in order to increase the viscosity and facilitate the insertion of the optic fiber. The third and final layer is placed over the fibers and is fully cured in the oven.

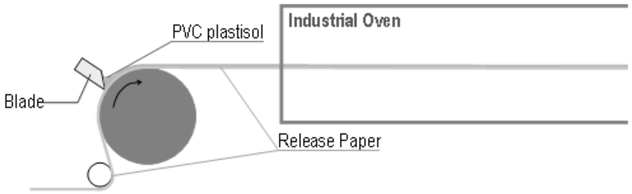

Figure 3 – Industrial process schematic.

III. RESULTS AND DISCUSSION

Figure 4 shows the functional prototype produced as previously described. The polymeric foil, 210x150 mm2 size has a Bragg sensor embedded in it. By visual inspection no damage is detected, being a good indicator of the fabrication process success. By touch, the fiber is not felt, sustaining the thought of a good integration level.

Figure 5 presents the reflected spectrum of the FBG sensor. The side lobes come from the grating fabrication process, resulting from radiation transmission function, and not from the integration process. The lobes can be later smoothed by apodization if necessary.

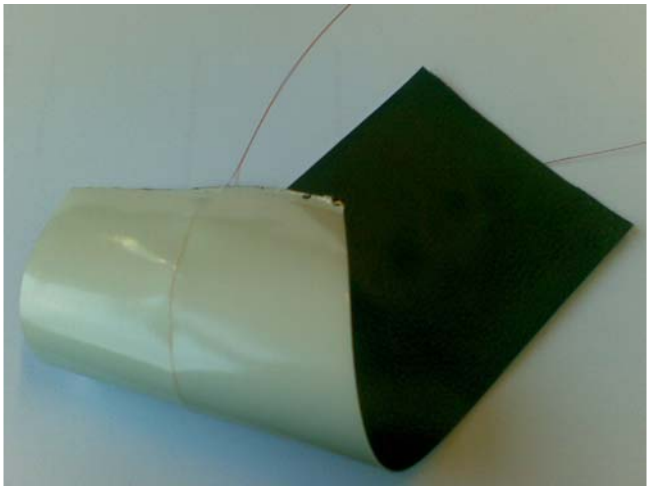

Figure 4 – Fabricated prototype.

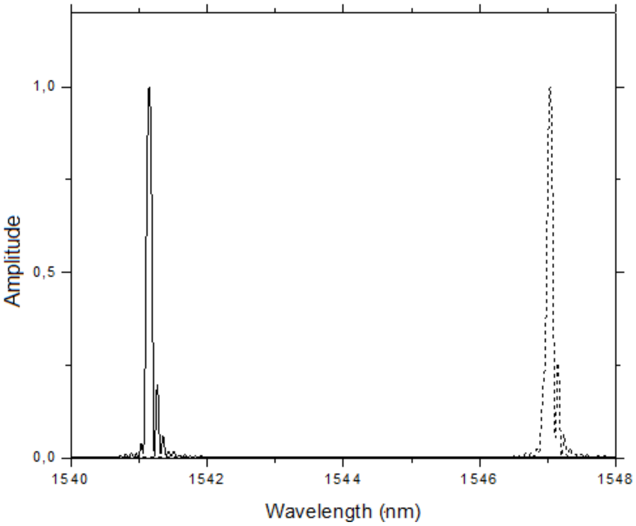

Figure 5 - Reflected spectrum from the FBG sensor for two distinct tensile forces.

When stretching the polymeric foil, the embedded FBG sensor follows the deformation and the reflected spectrum suffers a wavelength deviation. When the sample is released, the spectrum returns to the initial position.

Since one of the goals is to produce this type of foils with integrated sensors in a industrial environment, the restraints of the industrial process had to be evaluated. Considering that optical sensors are, in general, sensitive to temperature, one of the analyzed restraints was the fabrication process temperature. Several foils with integrated optic fibers were fabricated at different temperatures, from 200 to 240 ºC with 20 ºC steps, and at different cures durations, from 60 to 180 seconds with 30 seconds steps. It was found that the PVC from the polymeric foil did not stand temperatures above 240 ºC during 150 seconds. At the optic fiber level, all the Bragg sensors did support the temperature and the duration of the cure without presenting any sensitivity loss or damage. For the industrial process, these results do not present any restraints since, in general, the polymeric foils are fabricated at a temperature of 220 ºC for 60 seconds.

To better evaluate the performance of the produced model, the prototype was tested over a Instron® 4302 testing machine at the same time that the optical signal was being measured by a BraggMETER™ unit from FiberSensing company [8].

The prototype was cropped to the 50x100 mm size. Two tests were made over the model. One in which a displacement was applied at a constant increment until the model did not stand any more strain and the fiber snapped.

During this test, the model was subject to a displacement at the rate of 16 µm/s. As it is demonstrated over the graph (Figure 6), the wavelength deviation has a linear behavior from 0,4 % ahead. Two reasons for the non-linear part until de 0,4 % can be pointed. The testing machine does not have enough resolution for elongations lower than 400 µm, not providing precise elongation data, and in this case a test with a sample with double height may be used, since it duplicates the machine sensitivity. The polymeric foil does not transmit such little deformation to the fiber.

Besides this fact, the model was able to sustain the stretching of 1,62 % (strain), which is 1,62 mm of displacement. At this time, the fiber was subject to a load of 9,691 N.

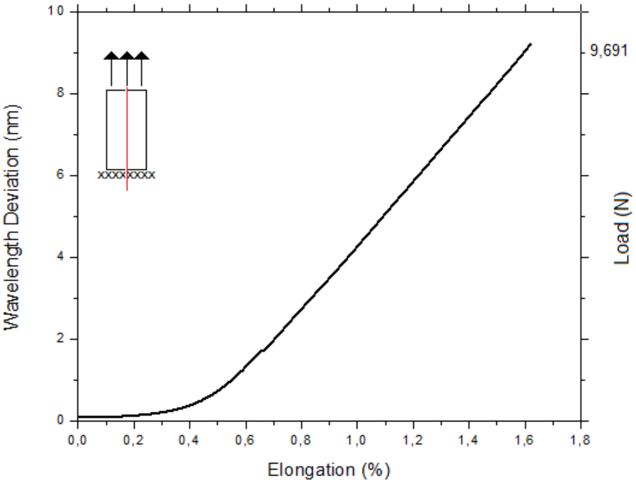

Figure 6 – Bragg response to applied displacements.

A displacement of 1,62 % with a wavelength deviation of 9,207 nm was measured and the sensitivity of the present model is 0,6 pm/µε (picometer per microstrain). To have a notion of the system resolution, if we consider a 1 meter long steel beam that has been stretched 1 mm, the wavelength deviation that would be measured is 0,6 nm. The determined sensitivity value provides information about the integration quality.

In another test, the displacement was applied in steps of 0,2 % (200 µm) and left at that state during a period of time, in order to evaluate the behavior of the fiber when subject to loads (Figure 7).

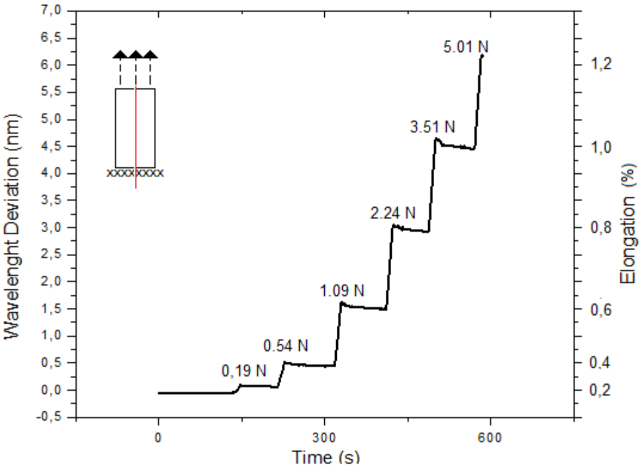

Figure 7 – Bragg response to applied displacement steps.

The applied displacement can incremented to see if the fiber slips over the polymeric foil. If this happens, the optical signal should start decreasing. In Figure 7, it can be seen a little bump after each step, but in seconds the optical signal stays constant. The small variation may be due to some vibration of the testing machine claw, since the model has a high sensitivity as determined before. The preservation of a constant value ensures that the fiber does not slip and that it is well embedded in the foil.

IV. CONCLUSION

The full integration of an optic fiber FBG sensor in a polymeric foil, using standard industrial fabrication processes was described in this paper. The prototype model presented an excellent behavior, 0,6 pm/µstrain. The integration of FBG sensors into the polymeric foil was evaluated in terms of the fabrication process temperature, integration level (adhesion of the fiber to the polymeric foil), measurement capabilities and sensor sensitivity. The structure showed good performance, namely, it had a linear behavior and, not only the spectrum shape continued the same during the force application, but also showed good repeatability, since it returned to its initial position and there was not any reduction of the signal amplitude. At the integration level analysis, the results demonstrated the successful integration of fiber sensor within the polymeric foil.

Integration of FBG based-sensors in PVC foils is demonstrated, promising production of large FBG based-sensors network in PVC foils and mass production in industrial environment.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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