Reinforced FBG Sensors Serve Demanding Applications

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Introduction

With a proven record over years of development, Fiber Bragg Gratings (FBG) sensors are being widely deployed for field applications in multiple industries. Many well-known advantages of FBGs over conventional electrical sensors include immunity to electromagnetic interference (EMI), chemically inert, small dimensions and low weight for easy integration and embedding into various materials, as well as high multiplexing capacity in a long single fiber lead.

To further increase the robustness and durability of the FBG sensing fiber, a well-established process is to coat the sensing fiber with the Glass Fiber Reinforced Polymer (GFRP) through an extrusion process. GFRP exhibits high strength and corrosion resistance, which makes the sensing fiber much more rugged for embedded applications in concrete and composite materials. These GRFP-FBG sensors are ideally suited for applications where there is concern that using cables with multiple construction layers may decrease the sensors' required sensitivity and response time and where using an unprotected fiber merely coated with acrylate, polyimide, ormocer, or other "first layer" materials is not enough physical protection for survivability.

GFRP-FBG Characteristics

The key for GFRP-FBG fibers is to ensure that the linear strain and temperature characteristic are preserved. Technica's GFRP sensing cable is designed with smart GFRP embedding process including an array of multiple FBG sensors embedded in GFRP ribbons or cables; the company's proprietary tight process control and advanced manufacturing technologies yield a very attractive and economically advantageous commercial solution. At its core, the optical cable consists of an array of FBG sensors. The outer layer of the cable is the GFRP coat which protects the optical fiber and ruggedizes the overall construction of the cable. A simple process for stripping the GFRP coating is also available for fiber splicing and connectorization at the factory or in the field.

Fig.1 illustrates the well-preserved linear dependence of wavelength shift on strain (sensor length change) of the GFRP-FBG, as evidenced by the linear-fit and the squared linear correlation coefficient (R^2) of nearly 1. The resultant strain sensitivity can vary depending on the fiber centering position, as compared to the typical 1.2 pm/$\mu\varepsilon$ strain sensitivity of the bare 125 μm cladding single-mode fiber (SMF) with 10 mm FBG length. As a consequence, each GFRP sensing cable must be calibrated. The GFRP coating also has the added advantage of serving as an effective amplifier for sensing vibrations (as in security fence monitoring). Imagine two FBGs at different wavelengths one meter apart in standard plain SMF. Without the rigid GFRP coating, a disturbance on the fiber near the middle of the two FBG sensors is unlikely to be sensed due to poor strain transfer. But with the GFRP coating in place, the strain effectively transfers through it and the embedded fiber, so that the FBGs will easily pick-up the vibration.

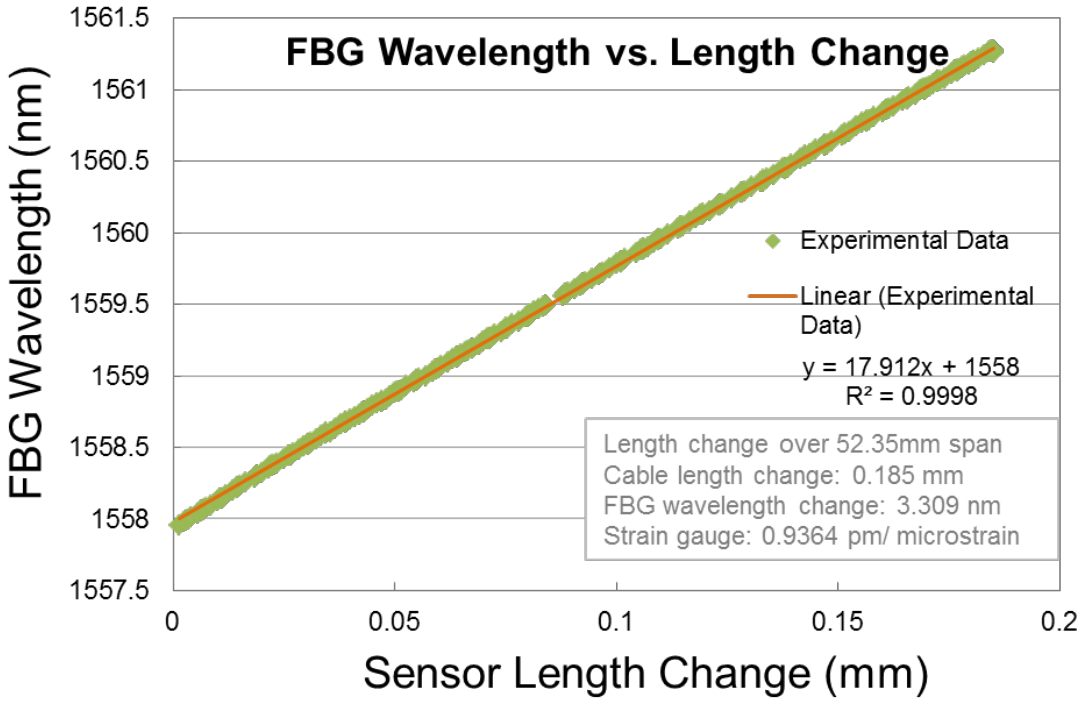

Fig.1. Linear dependence of wavelength shift on strain (length change) of the GFRP-FBG

As to the thermal characteristics, the linear temperature dependence is also preserved in the GFRP-FBG as shown in Fig.2, as evidenced by the R^2 of nearly 1. However, the resultant temperature sensitivity is essentially doubled from the typical 10 pm/°C to ~17 pm/°C. In some applications careful temperature compensation may be needed. For some perimeter security monitoring though, where only the relative strains/vibrations are required, the effects of temperature changes can easily be filtered out.

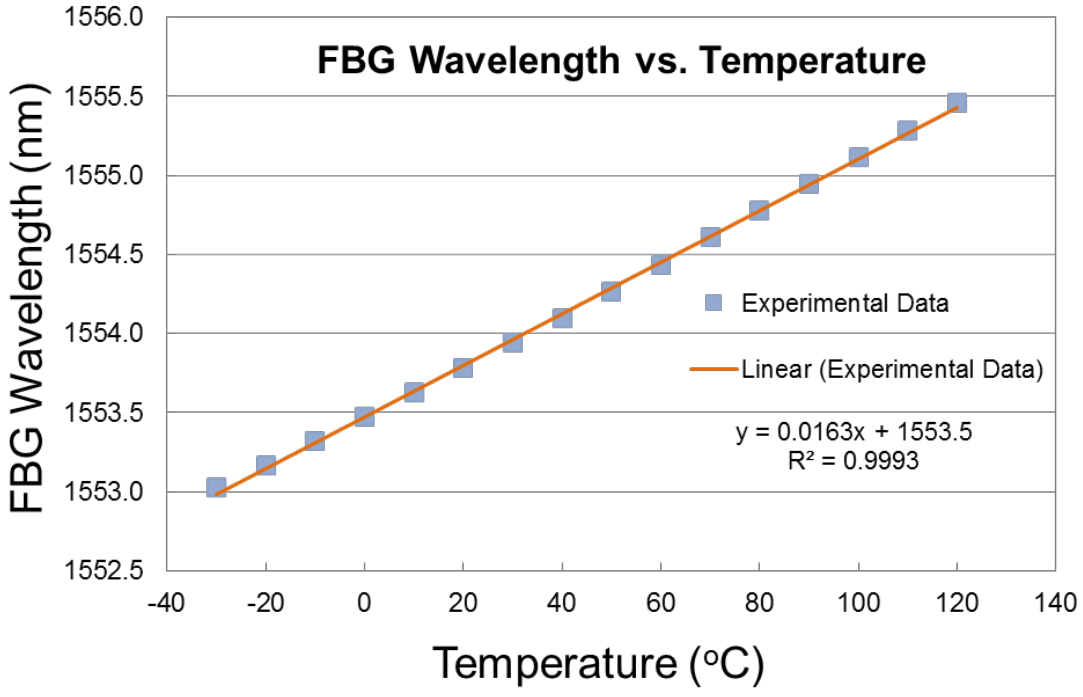

Fig.2. Linear dependence of wavelength shift on temperature of the GFRP-FBG

Sensing-Fiber Configurations

To accommodate different sensing configurations, the manufacturing process for the GRFP-FBG allows for significant variations in sensor wavelengths and distance spacing. Furthermore, to satisfy different embedding requirements and demanding environments, the fibers can be constructed in the forms of ribbons or cables, and terminated by different types of optical connectors.

Fig.3 illustrates an example of Technica's small-dimension, high-sensitivity T130 cable sensor designed for monitoring strain and temperature in surface mounted or embedded applications. These sensors allow easy handling and a much easier installation of a high number of sensing points over long distances when compared to the use of individual FBG based strain sensors, while elevating the degree of ruggedness to be consistent with, if not exceeding, industry expectations.

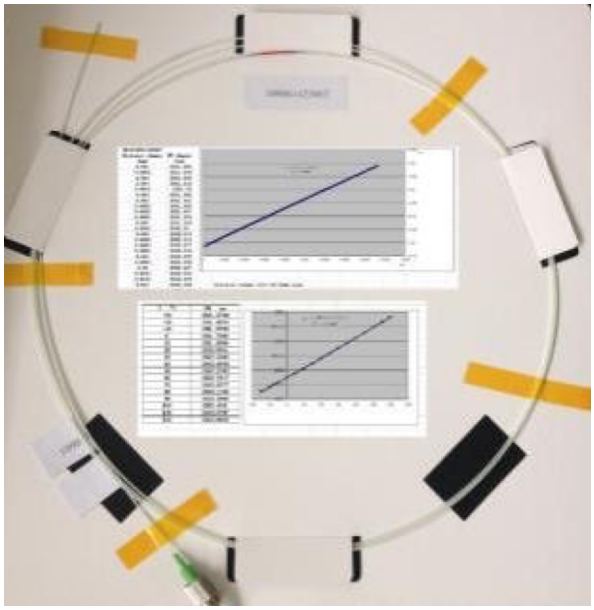

Fig.3. T130 GFRP-FBG sensing cable

For applications where a larger surface area of contact is needed for increased bonding strength and enhanced positioning, the T-120 sensing cable offers a ribbon geometry. The ribbon can contain multiple fibers, with 3 fibers in the current design as shown in Fig.4. While typically embedded in composite structures and concrete, the sensing ribbon is also well suited for surface-mounted applications such as pipelines, boilers, storage tanks, and vessels, where high sensitivity, high bonding strength, and sensor bending, are a must. Furthermore, surface shape monitoring with controlled fiber polarization is also applicable.

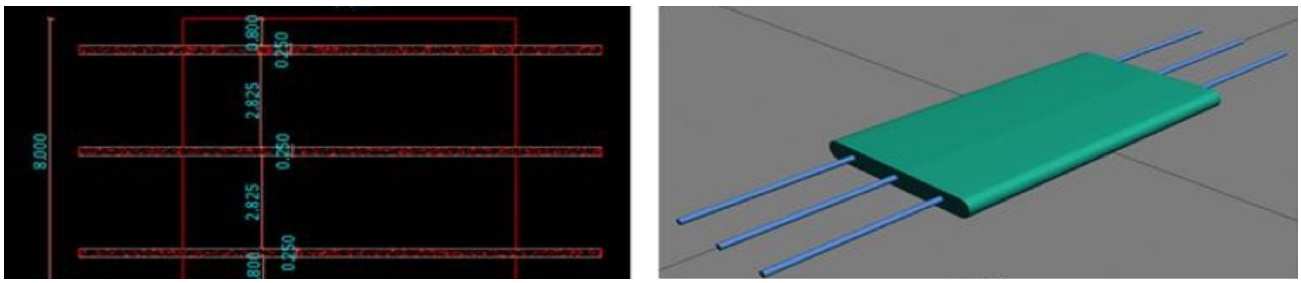

Fig.4. A schematic of T120 GFRP-FBG sensing ribbon containing 3 fibers

The rugged T-130 and T-120 sensing cables are typically used in applications where cable integrity must be maintained despite installation challenges such as the need to embed them in composite structures, roads, aircraft runway asphalt, and concrete. These very same GFRP cables are also well suited for surface-mount applications where high sensitivity is a must including security intrusion detection systems, tunnels, power cables, and various geotechnical applications. T130 cable sensors are typically packaged in spools ready for field field deployment (Fig.5).

Fig.5. T130 GFRP FBG cable sensors ready for field deployment.

For monitoring temperature in harsh environments the armored T140 high tensile-strength temperature cable sensor (Fig.6) is specifically designed to meet such demanding applications. In addition to the GFRP coating which protects the FBG sensors and strengthens the inner construction of the cable, the cable's final layer is the extremely rugged armored structure. The T140's high cable tensile strength and matching tensile modulus is ideally suited for demanding applications where cable integrity must be maintained despite installation challenges that include deployment of long cables and laying of cables over uneven and rough surfaces.

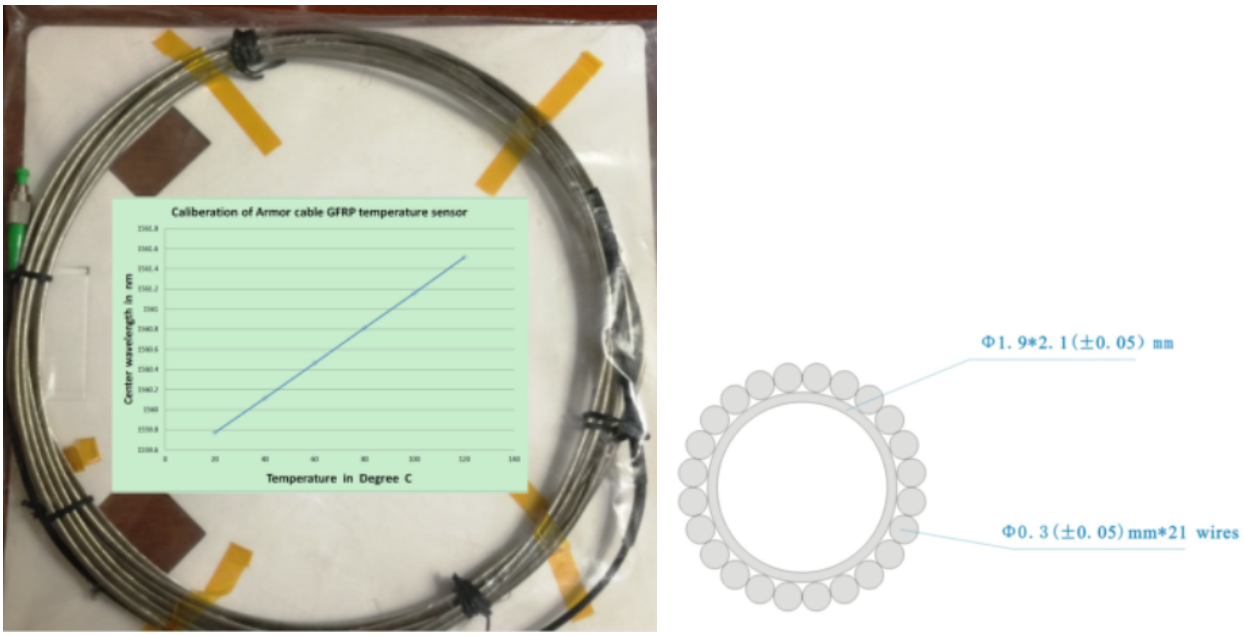

Fig.6. T140 high tensile-strength temperature cable sensor

The packaged GFRP-FBG sensor specifications in the Table below represent the most popular configurations. The manufacturing process allows for significant variations in construction including sensors at other wavelengths, termination by other types of optical connectors, as well as cable availability in custom lengths and with customer defined spacing between sensing points.

Parameter	Specifications
Wavelength / Tolerance	1460 to 1620 nm, +/-0.5
Strain Sensing Sensitivity	~1.2 pm/με
Reflectivity %	>70%
Reflection FWHM	0.2 to 0.3 nm
FBG Length	5 to 10 mm
Each FBG Sidelobe Suppression Ratio	Minimum 15 dB
GFRP Ribbon Width	10 mm, +/-1 mm
GFRP Ribbon Height	0.5 to 1 mm, 0.1mm steps
Cable Tensile Strength	>1100 MPa
Cable Tensile Modulus	>50 Gpa
Temperature Calibration Constant for -20C to 120C	~17 pm/°C
Optical Connector	FC/APC, FC/UPC

T120 sensing ribbon

Parameter	Specifications
Wavelength / Tolerance	1460 to 1620 nm, +/-0.5
Strain Sensing Sensitivity	~1.2 pm/με
Reflectivity %	>70%
Reflection FWHM	0.2 to 0.3 nm
FBG Length	5 to 10 mm
Each FBG Sidelobe Suppression Ratio	Minimum 15 dB
GFRP Cable Diameter	0.5 - 3 mm, 0.2 mm steps
GFRP Diameter Tolerance	+/- 0.05 mm
Cable Tensile Strength	>1100 MPa
Cable Tensile Modulus	>50 Gpa
Temperature Calibration Constant for -20C to 120C	~17 pm/°C
Optical Connector	FC/APC, FC/UPC

T130 sensing cable

Parameter	Specifications
Wavelength / Tolerance	1460 to 1620 nm, +/-0.5
Temperature Sensing Sensitivity	0.059 C/pm
Reflectivity %	>70%
Reflection FWHM	0.2 to 0.3 nm
FBG Length	5 to 10 mm
Each FBG Sidelobe Suppression Ratio	Minimum 15 dB
Armored Cable Diameter	2.1 mm
GFRP Cable Diameter	0.9 mm
Cable Tensile Strength	>1100 MPa
Cable Tensile Modulus	>50 Gpa
Temperature Calibration Constant for -20C to 120C	~17 pm/C
Optical Connector	FC/APC, FC/UPC

T140 armored cable

Examples: Sensor Response in Concrete

While many examples of successful GFRP-FBG cable sensor applications exist, the illustrations and example below aim to inspire researchers, experimental engineers, and field specialists towards further broadening the adoption of this technology for greater benefits to the industries they serve.

Figs. 7 and 8 show the use of the T130 GFRP FBG cable array for testing concrete configurations to be used in the construction of next generation buildings.

Fig.7. T130 GFRP-FBG cable sensor tied to reinforcement bar before pouring concrete.

Fig.8. T130 GFRP-FBG cable sensor exiting concrete for connection to optical monitoring instrument.

An example of the T130 sensing cable response after embedding in concrete is illustrated here. The sensing cable was buried and set in place during concrete pouring as shown in Fig. 9. The sensor response was measured over a force load up to 100K Newton (N) and over a span of 28 days.

Fig.9. T130 sensing cables buried in concrete ready for measurements

Fig.10 shows the integrity of the reflection spectrum of an example FBG sensor over the 100KN test load 3 days after concrete embedding.

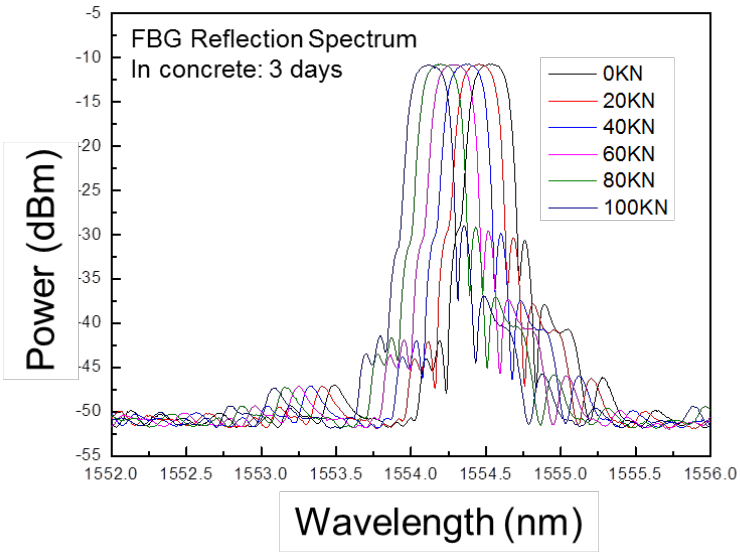

Fig.10. Spectrum of an exampleT130 FBG sensor

The sensing cable strain response was measured daily over the span of 28 days, and Fig.11 compares the stress (σ) vs. strain (ε) on day-3 and day-28. Note the wider stress and strain measured on later days. Reliable and consistent performance provides valuable material behavior insights to the engineering team.

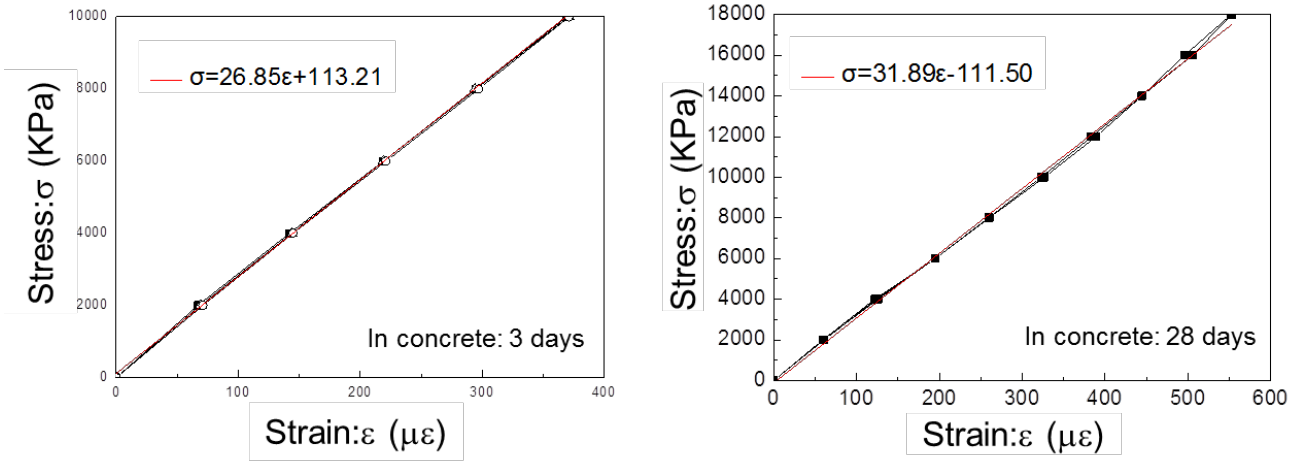

Fig.11. Stress (σ) vs. strain (ε) on day-3 and day-28

Summary

The innovative and reliable designs of these GFRP-FBG sensing ribbons and cables eliminate the fragility and handling challenges typically associated with single coated fibers and enable significant field installation productivity improvements. They are particularly suitable for demanding projects that require both low cost per sensing point and stable operation over the long term, as in civil engineering, geotechnical applications, energy, aerospace, marine, railways, advanced land vehicles, industrial, security, fire monitoring, and mining, as well as for use in materials development and testing labs across many industries.