White Paper

Optical Fiber Sensors vs. Conventional Electrical Strain Gauges for Infrastructure Monitoring Applications

by
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Virtually every type of public infrastructure, including bridges, pipelines, tunnels, foundations, roadways, dams, etc., is subject to factors that can degrade it or lead to malfunctions. These structural problems can be the result of deterioration, improper construction methods, seismic activity, nearby construction work, etc. Although electrical strain gauges have long been used for monitoring structural changes, they sometimes lack the durability and integrity necessary to provide accurate, actionable information over extended periods.

Optical fiber strain gauges that are based on fiber Bragg gratings (FBGs) operate on very different principles than those that govern traditional electrical strain gauges. In simplified terms, a fiber Bragg grating is a microstructure (typically a few millimeters long) created by modifying a standard single-mode telecom fiber, germanium-doped, with a UV laser. This microstructure creates a periodic variation in the refractive index of that optical fiber. As light travels along the fiber, the Bragg grating reflects a very narrow range of wavelengths; all of the other wavelengths are transmitted through the grating. The center of this band of reflected wavelengths is known as the Bragg wavelength **(Figures 1 and 2)**. Under stress, the period of an FBG increases due to the physical stretching or compression of the optical fiber. This change results in a shift in the Bragg wavelength, which is then detected and recorded by the interrogator (i.e., data acquisition system).

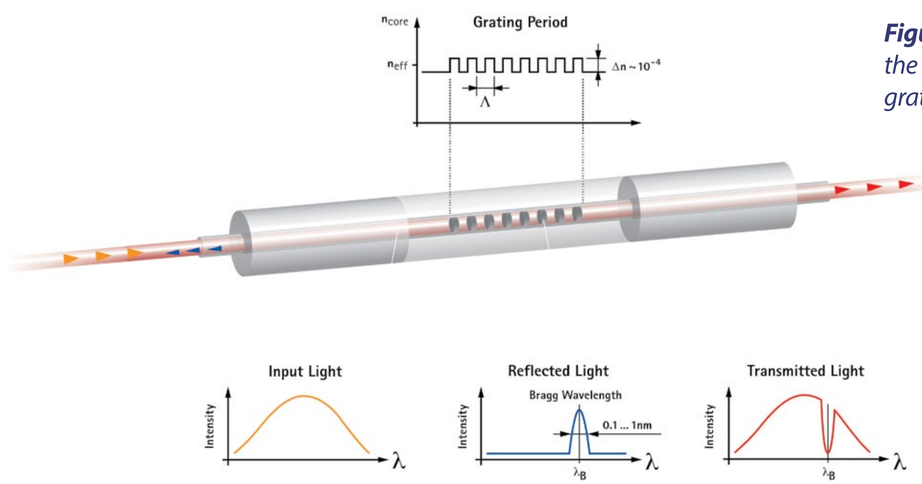

***Figure 1.** The principle underlying the operation of fiber Bragg grating (FBG) strain gauges.*

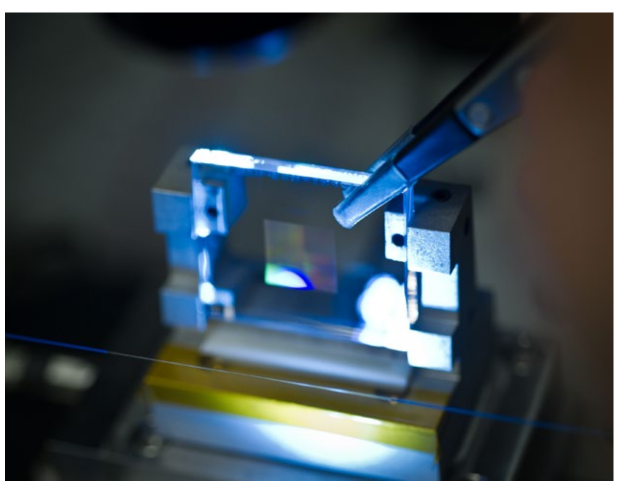

***Figure 2.** Manufacturing a fiber Bragg grating using the phase mask method. The phase mask creates two orders of refraction of the incident UV light, producing a pattern of maximum and minimum interferences at the core of the fiber. The fiber's refractive index is permanently altered according to the intensity of the light to which it is exposed. This precise spacing of different optical properties within the fiber builds the Bragg grating.*

In addition to strain, fiber Bragg gratings are sensitive to temperature. This allows the usage of FBGs to monitor temperature, but it also means that it is a good practice to combine a temperature sensor with a strain sensor to allow for compensation of the temperature's effect on the strain sensor. In addition to strain and temperature, FBG-based sensors can be used in transducers to monitor a variety of other parameters, such as tilt, acceleration, pressure, etc.

FBG-based optical fiber strain gauges offer a variety of advantages over electrical strain gauges. For example, they provide long-term signal stability and system durability; even at high-level vibration loads, such as on heavily traveled roadways and bridges, they are far less subject to mechanical failure. Distance and cable length have virtually no impact on measurement accuracy; because optical fiber-based systems experience only minimal signal attenuation, the integrity of the data remains high, even if the data acquisition system must be located several kilometers away from the most distant sensor. Optical fibers are much thinner and lighter than copper conductors, so the connection leads are much lighter. A single measuring lead allows connecting many sensors with different base wavelengths, reducing the level of wiring effort required. Their immunity to electromagnetic and radio-frequency interference (EMI/RFI) can be invaluable in structures such as railway bridges or tunnels for electrically powered trains, which can produce intense electromagnetic fields.

The use of FBG sensors allows for drastic reductions in the amount of cabling a monitoring system requires due to the intrinsic high multiplexing capability of the technology, which ensures minimal impact on the structures being monitored. In this context, "multiplexing" refers to the ability to connect many optical sensors of different types to a single optical fiber, which reduces network and installation complexity. Sensor arrays with dozens of sensors can be pre-assembled to simplify installation; they are easy to glue to surfaces and materials, spot weld to structures or components, attach to or cast into concrete as it is poured. Their small size and weight also make them particularly attractive for locations with limited space and embedding applications, such as in composite structures. Their relatively low cost per sensor, ability to combine multiple sensor types in a single cable, and no need for multiple interrogators in the system makes them a cost-effective solution for medium/large projects.

They are also well suited for use in harsh environments. In addition to their EMI/RFI immunity, they offer high resistance to degradation due to water and humidity, salt, temperature extremes, and high pressure (up to 400 bar). They're also safe for use in potentially explosive atmospheres and high voltage areas.

Unlike metallic foil strain gauges, FBG sensors are referenced independently from the interrogator/acquisition system. Instead, they are based on the measurement of an absolute parameter—the Bragg wavelength—which is independent of power fluctuations and changes only when strain (or a change in temperature) is applied. The optical interrogator itself, which measures the values generated by the sensors, also has a built-in reference that works like a "ruler" for accurately determining the received wavelength values. This internal reference allows calibrating the interrogator with every measurement performed.

Optical fiber sensor systems offer infrastructure engineers fatigue limits that are more in line with the fatigue behavior of modern structural materials. Lightweight carbon fiber sheets, for example, feature higher fatigue and strain limits than traditional structural materials. Even commonly used materials like steel, concrete, and wood are increasingly being modified to optimize their fatigue behavior, so they're also demanding monitoring systems designed with higher fatigue limits.

Figure 3 illustrates a recent example of the use of optical fiber sensing in infrastructure monitoring. HBM FiberSensing helped design a sensor network for real-time monitoring of tunnel deformations and convergences in an operating metro line in São Paulo, Brazil, while a skyscraper was under construction nearby. The tunnel monitoring system was required during the excavation process and construction of a support wall for the skyscraper to ensure the operation of the metro line was not interrupted and the safety of metro riders wasn't compromised. The Extensometric Method for Determining Convergences in Tunnels employed for this project uses FBG-based sensors to measure strain at different points along the tunnel contour and converts them into displacement of the tunnel support.. It also allows for the quantification of convergences of the support and its geometric evolution over time.

Figure 3. *Installation of a measuring section for tunnel monitoring.*

Two sections of the tunnel were monitored with seven measuring points each, with one strain and one temperature sensor at every measuring point. An FS22 rack-mountable BraggMETER with four optical channels was used to interrogate all sensors, with data being acquired once per minute, then processed and saved to a database. A 19-inch rack was installed nearby to protect the measurement unit, the server PC, the UPS, and an internet connection. Measured wavelengths were computed in order to have strain measurements compensated for the thermal effect on the Bragg wavelength and convergences were estimated with the method algorithm. More details on this project, including a system schematic, are available in a paper presented at the 15th International Conference on Experimental Mechanics, "Remote Monitoring of São Paulo Metro Tunnel Deformations Using Fiber Optic Based Sensors," available online at: http://paginas.fe.up.pt/clme/icem15/ICEM15_CD/data/papers/3189.pdf.

Similarly, an HBM FiberSensing strain and temperature measurement system is being used for long-term monitoring of a 1.1km cable-stayed bridge over the Rhumel River in Constantine, Algeria. The system was installed in parallel with conventional technology sensors and data acquisition devices and integrated as a full Structural Monitoring System (SHM). Sensors were delivered pre-assembled in arrays of strain and temperature sensors to be cast inside the concrete. Each end of the array had an optical connector. Long optical break-out cables with four fibers each and connectors on each end were used for linking the several array locations. This pre-assembly and preparation work improved installation efficiency, not only because of fewer cables but because the use of connectors ensured that the installation did not require the use of special manpower or equipment. One four-channel BraggMETER interrogator collects simultaneous data from 22 strain sensors and 18 temperature sensors for a total of 40 FGB-based sensors. The interrogator is installed in conjunction with the other data acquisition systems and controlled at the same time using its available LAN interface.

Figure 4. *Embedded strain sensor being installed on a bridge's deck before the concrete is poured.*

Although engineers may have decades of experience in using electrical strain gauges in structural monitoring, these applications demonstrate how optical fiber sensors can offer a variety of economic and performance advantages. To learn more about the advantages optical fiber sensors have over conventional electrical strain gauges, view "Infrastructure monitoring with optical fiber sensors: different, not difficult," available online at https://hbm.wistia.com/medias/kg0m61fyxt/. For more in-depth information on the principles underlying FBG-based optical fiber sensors, visit http://www.hbm.com/fibersensing.

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HBM has 27 subsidiaries and sales offices in Europe, America and Asia. HBM also has representatives in another 40 countries around the world. In addition to headquarters in Darmstadt, Germany, other HBM production facilities are located in Marlborough, Massachusetts, and Suzhou, China.

Biographical Note

Cristina Barbosa received the Lic. and M.Sc. degrees in civil engineering, specializing in structures, from the Faculty of Engineering of Porto University (FEUP), Portugal, in 2004 and 2009, respectively. Presently, she is Product Manager at HBM FiberSensing. HBM FiberSensing was created in 2014 after HBM group acquired FiberSensing, an INESC Porto spin-off company developing fiber optic sensors and systems for different markets, such as structural health monitoring. At FiberSensing, she served in a variety of positions, including application engineer, product development and test engineering, and sales engineer. Previously, she was an investigator at Laboratório de Engenharia Sísmica e Estrutural from FEUP in the area of structural health monitoring. She is the author/co-author of several communications and papers in the field of structural health monitoring using fiber Bragg grating technology.