Fiber-Optic Sensing Technologies

Introduction to Fiber-Optic Sensing

The fiber optics and optoelectronics industry has experienced a tremendous amount of innovation over the past four decades. Initially conceived for medical endoscopic applications, optical fibers were considered in the mid-1960s as an adequate technology for telecommunications applications. Since then, light wave communications systems have become the preferred and standard method to transmit vast amounts of data over long distances, significantly reducing optical component prices and improving quality.

By taking advantage of these economies of scale, fiber-optic sensors and instruments have moved to broad usage and applicability in field applications such as structural health monitoring. Fiber-optic sensors offer the same benefits that optical fibers deliver to the telecommunications industry. They are immune to EMI, nonconductive, electrically passive, low loss, high bandwidth, small, lightweight, relatively low cost, and so on.

At the core of optical sensing technology is the standard optical fiber – a thin strand of glass that transmits light within its core. An optical fiber is composed of three main components: the core, the cladding, and the buffer coating, as shown in Figure 1. The cladding effectively "reflects" stray light back into the core, ensuring the transmission of light through the core with minimal loss. This is essentially achieved with a higher refractive index in the core relative to the cladding, causing a total internal reflection of light. The outer buffer coating serves to protect the fiber from external conditions and physical damage. It can incorporate many layers depending on the amount of ruggedness and protection required.

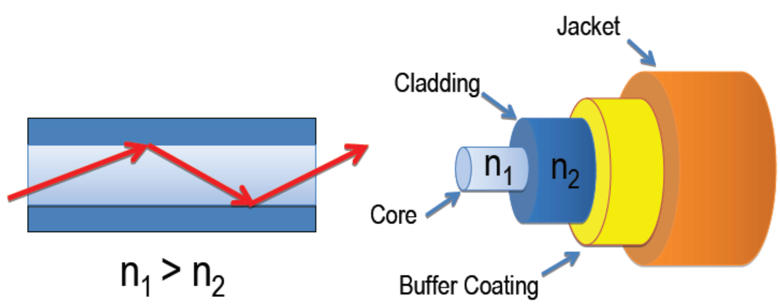

Figure 1. *Schematic of an Optical Fiber*

Fundamentally, a fiber-optic sensor works by modulating one or more properties of a propagating light wave, including intensity, phase, polarization, and frequency, in response to the environmental parameter being measured. In its simplest form, an optical fiber sensor is composed of a light source, optical fiber, sensing element, and detector.

A variety of optical sensing technologies has been developed over the years and is now readily available on the market. Among these are Fabry-Perot interferometers, fiber Bragg gratings (FBG), and distributed sensors based on Rayleigh, Raman, and Brillouin optical scattering techniques. Depending on the light modulation and effect used to measure physical phenomena, these optical sensing technologies can be classified as the following:

- Intensity
    - Attenuation of light
- Interferometric
    - Phase difference between two light waves (Sagnac, Michaelson, Mach-Zehnder)
- Resonant
    - Optical resonant frequency of an optical cavity (Fabry-Perot)
- Distributed
    - Backscattering (Rayleigh, Raman, Brillouin)
- Polarimetric
    - Polarization state of light wave
- Spectral Interference
    - Frequency of light wave interfering with a periodic structure (fiber Bragg grating)

Based on their topology and configuration, fiber optic sensors (FOSs) can be further classified as either *single-point*, *multi-point,* or *distributed*. A single-point sensor typically has the sensing portion of the fiber located at the tip. A multi-point FOS consists of two or more sensing regions along the length of a fiber, where each region can detect the same or a different parameter. These sensing regions can be physically spaced from a few millimeters to several meters away, depending on the application requirements. Truly distributed fiber-optic sensing systems use the entire fiber length to sense one or more external parameters, which can be on the order of several tens of kilometers. This is a capability unique to fiber-optic sensors and one that cannot be easily achieved using conventional electrical sensing techniques. Table 1 compares the various optical sensing technologies discussed.

Technologies	Topology	Range	Temperature	Strain	Pressure	Vibration
Fabry-Perot	Single-Point	< 10 km	Yes	Yes	Yes	Yes
FBG	Multi-Point	< 50 km	Yes	Yes	Yes	Yes
Rayleigh	Distributed	< 70 m	Yes	Yes	No	No
Raman	Distributed	< 20 km	Yes	No	No	No
Brillouin	Distributed	< 50 km	Yes	Yes	No	No

Table 1. *Comparison of Optical Sensing Technologies (distances are approximate)*

Distributed Fiber-Optic Sensors

Transmission loss, also known as attenuation, was historically a limiting factor to the development of optical telecom systems. A significant reduction in the attenuation loss propelled optical fiber to become the dominant technology for high-speed, long-distance telecommunication. Although low, attenuation still exists in modern optical fibers, primarily caused by fiber scattering and absorption due to in-homogeneities in the fiber. Optical time-domain reflectometers (OTDRs) are used to evaluate the quality of the optical fibers and connectors by sending a narrow pulse of light and measuring the resulting backscatter. The same scattering phenomena and OTDR technology in telecom can be used for optical sensing.

The concept of “distributed sensors” was first introduced in the 1980s, measuring the scattered light at every location along the fiber. Different types of scattering exist, including Rayleigh, Brillouin, and Raman scattering.

Rayleigh, the most dominant type of scattering, is caused by density and composition fluctuations created in the material during the manufacturing process. Rayleigh scattering occurs due to random microscopic variations in the index of refraction of the fiber core. When a narrow pulse of light is launched into a fiber, the variation in Rayleigh backscatter can help determine the approximate spatial location of these variations. Although Rayleigh scattering is relatively insensitive to temperature, it can still be used as a distributed sensing technique for temperature and strain, and it is typically effective at distances up to 70 m. Rayleigh backscattering is often regarded as a promising and emerging technology.

Raman, another type of scattering, is caused by the molecular vibrations of glass fiber stimulated by incident light. The resulting scatter has two wavelength components, one on either side of the main exciting light pulse wavelength, called Stokes and anti-Stokes. The ratio between Stokes and anti-Stokes is used for temperature sensing, and is immune to strain. This technology is popular in downhole oil and gas applications for profiling temperature variations in oil wells.

Finally, a third type of scattering is Brillouin, which stems from acoustic vibrations stimulated by incident light. To satisfy the requirement of energy conservation, there is a frequency shift between the original light pulse frequency and the Brillouin scattering wave. This frequency shift is sensitive to temperature and strain, so it enables the profiling of temperature and stress variations throughout the length of the fiber. However, differentiating between temperature and strain can be difficult. Special sensor packaging and the combination of Brillouin with other sensing technologies (such as Raman or FBG, which are covered later in this paper) can help separate the two physical phenomena.

All three backscattering technologies are well-suited for monitoring slow-changing parameters, so you can use them to perform static measurements where trends along the fiber are the primary focus. With backscattering optical sensing solutions, you often face a trade-off between measurement resolution, spatial resolution, and sampling rate. Higher spatial and measurement resolutions require lower sampling rates, hovering anywhere between 1 sample per second to 1 sample per hour over a distance of up to 30 km. Spatial resolution (physical location on the fiber) is typically limited to ~1 m; however, you can improve it through signal processing and even lower sampling rates.

For higher speed, more accurate point sensor measurements, you can turn to Fabry-Perot interferometers and fiber Bragg gratings.

Fabry-Perot Interferometer

Fabry-Perot (FP) interferometer sensors are essentially composed of two parallel mirrors separated by a cavity (see Figure 2). Intrinsic fiber Fabry-Perot interferometric (FFPI) sensor mirrors are separated by a continuous segment of single-mode fiber, while extrinsic Fabry-Perot interferometric (EFPI) sensor mirrors are separated by an air gap. In both cases, when light is sent into the sensor, multiple beams of light interfere between the two mirrors to create a series of peaks in the resulting optical spectrum. The spacing between the spectrum peaks changes in relation to the change in spacing between the mirrors, which in turn could vary in relation to a physical phenomenon. Hence, any changes in the gap distance between the mirror surfaces of the FP produce a modulation of the output signal current. This modulation is sinusoidal, gradually decreasing in amplitude as the distance increases. The real-time monitoring of changes in the phase of the output fringes thus yields information in the air-gap separation between the end faces of the two fibers in the sensor head.

Owing to the high sensitivity of the fringe phase relative to the air-gap, the basic EFPI sensor geometry or its variations can be very favorable to the measurement of a variety of phenomena that can be related to microdisplacement. This method enables a single-point sensor measurement per fiber, typically of temperature and pressure. Because of their compact size and relative simplicity, these sensors can be made very small for medical applications or can be ruggedized as pressure transducers in downhole oil and gas applications.

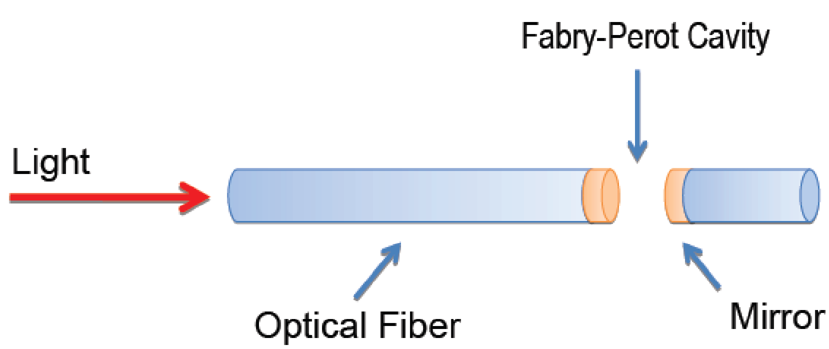

Figure 2. *Basic Configuration of a Fiber Fabry-Perot Interferometer Sensor*

Fiber Bragg Gratings

One of the most versatile and broadly deployed optical sensors is the fiber Bragg grating (FBG), which reflects a specific wavelength of light that shifts in response to variations in temperature and/or strain. Since their fortuitous discovery by Ken Hill back in 1978 [3] and subsequent development by researchers at the Canadian Research Center, United technologies, 3M, and several others [5], intra-core fiber gratings have been used extensively in the telecommunications industry for dense wavelength division multiplexing, dispersion compensation, laser stabilization, and more. But given their intrinsic capability to measure a multitude of parameters such as strain, temperature, and pressure, coupled with the flexibility of using them as single-point or multi-point sensing arrays, FBG devices have been recognized since their early beginnings as ideal sensing elements. FBGs perform direct transformation of the sensed parameter to optical wavelengths – independent of light levels, connector, or fiber losses – or other FBGs at different wavelengths.

This technology can address a wide range of applications because of its ability to measure many types of physical phenomena and daisy chain dozens of sensors along a single optical fiber. This makes it an ideal technology for replacing conventional electrical sensors.

An FBG is a wavelength-dependent optical filter/reflector formed by introducing a periodic refractive index structure – with physical spacing on the order of a wavelength of light – within the core of an optical fiber. When a broad-spectrum light beam is sent to an FBG, reflections from each segment of alternating refractive index interfere constructively only for a specific wavelength of light called the Bragg wavelength, as depicted in Figure 3. The reflected light signal is a very narrow peak (width ranging from a fraction of 1 nm to a few nanometers) and is centered at the Bragg wavelength that corresponds to twice the periodic unit spacing of the gratings. This effectively causes the FBG to reflect a specific frequency of light while transmitting all others. Any change in the modal index or grating pitch of the fiber caused by strain, temperature, or polarization changes results in a Bragg wavelength shift.

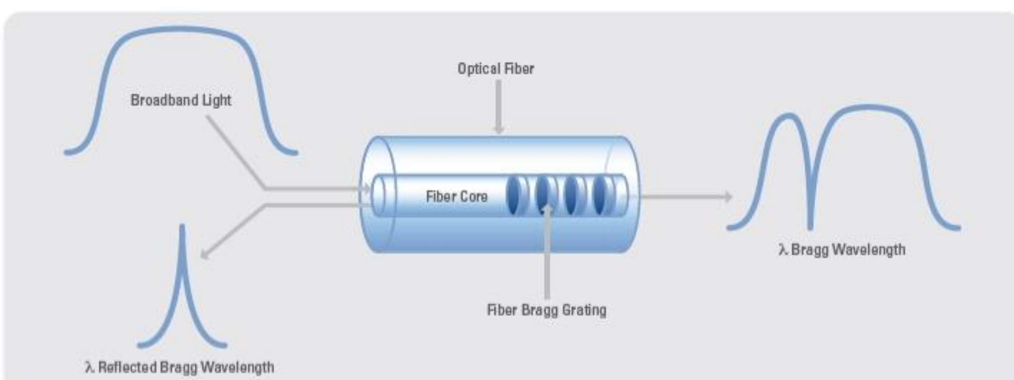

Figure 3. *Operation of an FBG Optical Sensor*

Because the peak Bragg wavelength is a function of the spacing between the gratings, FBGs can be manufactured with various Bragg wavelengths, which enables different FBGs to reflect unique wavelengths of light. Thus you can daisy chain several FBGs with unique Bragg wavelengths on a single, continuous optical fiber.

The number of sensors that you can incorporate within a single fiber depends on the wavelength range of operation of each sensor and the total available wavelength range of the optical sensor interrogator (OSI). Because wavelength shifts due to strain are typically more pronounced than temperature, FBG strain sensors are often given an ~5 nm range, while FBG temperature sensors require ~1 nm. Because typical interrogators provide a measurement range of 40 to 80 nm, each fiber array of sensors can usually incorporate anywhere from one to more than 80 sensors – as long as the reflected wavelengths do not overlap in the optical spectrum (Figure 4).

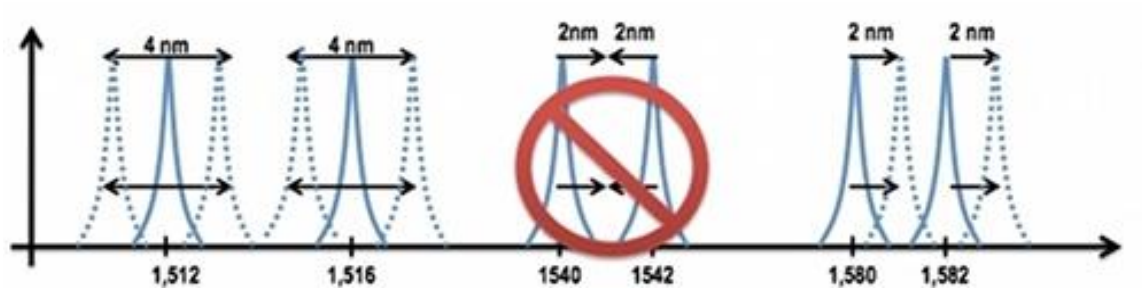

Figure 4. *Each FBG optical sensor in an array must occupy a unique spectral range.*

The selection and use of FBG optical sensors is simple, with an installation process almost identical to the established methods originally created for electrical sensors. It is often easier when compared to traditional electrical sensors: you can glue, weld, and embed FBG sensors while having fewer cables to manage and no noise, isolation, and/or shielding considerations to address. Also, you can choose from a variety of optical cables, from simple low-cost cables to rugged deep sea cables, to meet your most stringent requirements.

Learn more about the FBG optical sensing technology.

Benefits of FBG Optical Sensing

Optical sensors are nonconductive, electrically passive, immune to EMI, lightweight, and noncorrosive. This means you can safely perform sensor measurements near high voltages, high sources of electromagnetic interference, and in explosive environments.

Because of the aforementioned features of FBG technology and its multi-point form factor, FBGs are an ideal alternative to conventional electrical sensors. Contrary to technologies like electrical foil strain gages, the behavior of FBG optical sensors is very stable over time, making it an excellent option for long-term structural health monitoring, which requires correlating measurements over decades. FBG optical sensing systems can also interrogate sensors over long distances with the use of powerful lasers and low-loss fiber arrays. With an industry-leading OSI like the NI PXIe-4844, you can achieve a temperature resolution of ~0.1 °C and strain resolution of ~0.7 microstrain. In addition, you can interrogate sensors over 10 km away from the measurement system.

Overall, the benefits of optical sensing technologies can help you meet many sensing application challenges that cannot be easily addressed with conventional electrical sensors. FBG optical sensors are powerful and versatile yet simple measuring tools that can be easily adopted in a broad variety of applications.

References

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