Optical Fiber Technology

An introduction to the fundamentals.

What is fiber optics?

An optical fiber is a circular waveguide that takes the form of a long, thin strand of glass about the diameter of a human hair. This fiber contains two concentric glass regions with slightly different refractive indices. The refractive index is the ratio of the speed of light in a vacuum to its speed in the glass fiber medium. The center of the fiber through which most of the light travels is called the fiber core. The outer region, having a lower refractive index than the inner region, is called the cladding. The outer dimension of a standard glass optical fiber is 0.125 mm or 125 µm. A surrounding plastic coating is normally applied to protect the glass fiber. Additionally, an encasing cable structure to protect the optical fiber during installation and operation is often applied.

Two basic optical fiber types exist: single-mode or multi-mode. The main difference is the dimension of the fiber core. A single-mode fiber typically has a core diameter of 10 µm, which allows only one mode of light at any time to propogate through the core. Multi-mode fiber has a much larger core (normally a 50 mm or 62.5 µm diameter), allowing hundreds of modes of light to move through the fiber simultaneously.

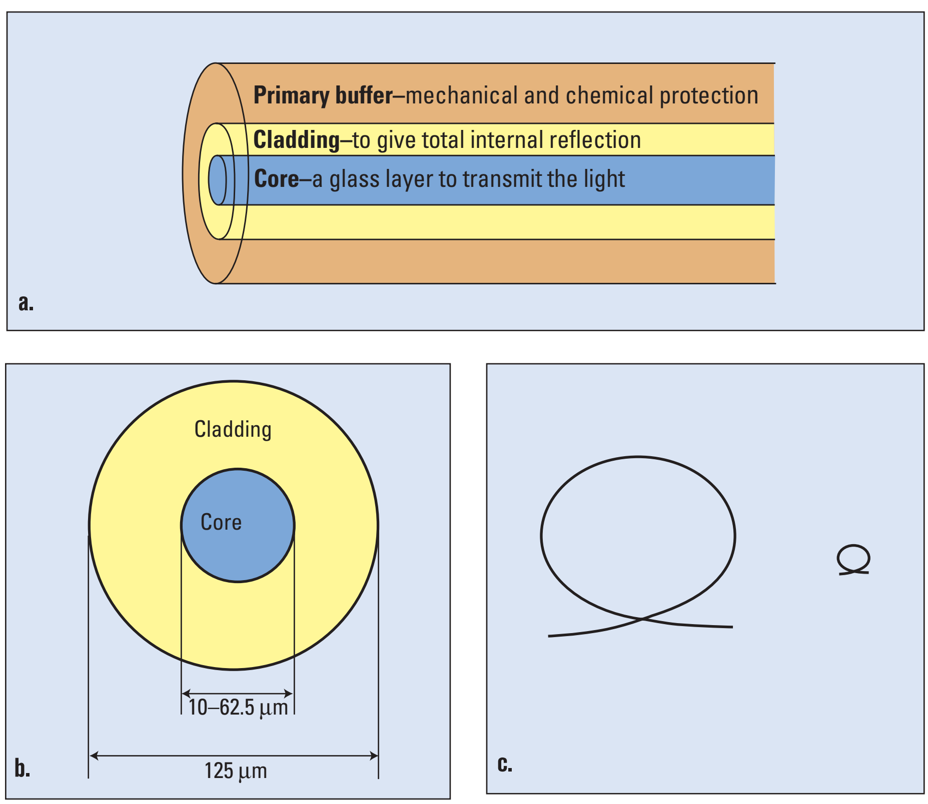
In sensing systems, single-mode fibers are normally used because they can maintain spatial, temporal and spectral integrity of each optical signal during longer distances. However, in the case of distributed temperature-sensing measurements (distributed temperature sensing system), multi-mode fibers are most common.

The most frequently used splicing technique for optical fibers is fusion splicing, where the two fiber ends to be spliced are melted together. Splice loss less than 0.1 dB can easily be achieved. A huge variety of optical connectors exist where the fiber cores are positioned during mating with sufficient accuracy (+/- 1µm) to achieve connector loss less than 0.5 dB.

How does an optical fiber transmit light?

The optical fibers configuration allows for total internal reflection of light at the boundary between core and cladding. Light reflects (bounces back) or refracts (alters its direction while penetrating a different medium), depending on the angle at which it strikes the core/cladding boundary.

This principle is the cornerstone of how optical fiber works. Lightwaves are guided through the core of the optical fiber in much the same way that radio frequency (RF) signals are guided through coaxial cable. The lightwaves are guided to the other end of the fiber by being reflected within the core. Controlling the angle at which the light waves are transmitted makes it possible to control how efficiently they reach their destination. As a result, the compo-

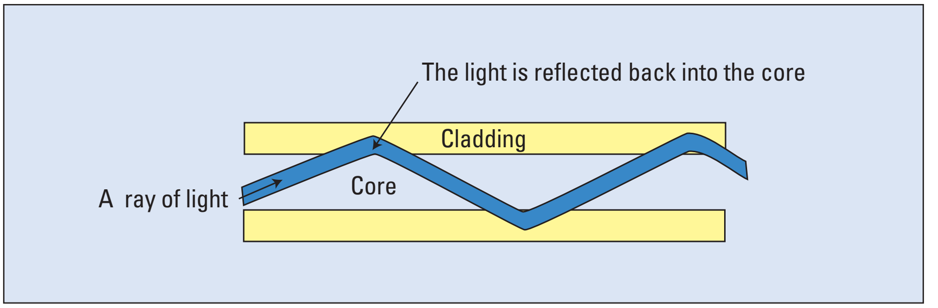


a) The completed optical fiber showing fundamental component layers. b) The typical size of an optical fiber showing relative diameters of core and cladding. c) A typical optical fiber can be bent as tight as that on the right before it breaks sition of the cladding glass relative to the core glass determines the fiber's ability to transmit light. The difference in the index of refraction of the core and the cladding causes most of the transmitted light to bounce off the cladding glass and stay within the core. In this way, the fiber core acts as a waveguide for the transmitted light.

Because the cladding absorbs or scatters only negligible light from the core, the light wave can travel great distances. However, when light propagates in the core of an optical fiber, some small part of the light is lost due to scattering phenomena. The extent that the signal degrades depends on the purity of the glass and the wavelength of the transmitted light. This loss or attenuation is normally quoted in a logarithmic loss per unit fiber length, i.e. in dB per fiber length. At wavelengths typically used in remote sensing systems, attenuation in a single-mode fiber is about 0.2 dB/km. The attenuation in a multi-mode fiber is somewhat higher.

Three high level components are involved in optical sensing systems:

- the first is the light source in the transmitter. This source may be modulated by signals received from an electrical control system. In an oil field optical sensing system the light source resides at the surface in an opto-electronic instrumentation package;
- Second is the fiber optic cable, which can consist of a single strand or multiple strands of specially manufactured optical fiber packaged to form a cable. Each fiber optic strand is as thick as a human hair, but in oilfield sensing applications the actual cable measures a quarter inch in diameter after the strands have been wrapped in protective coverings. This quarter inch cable is clamped to the completion tubing for downhole sensing applications; and



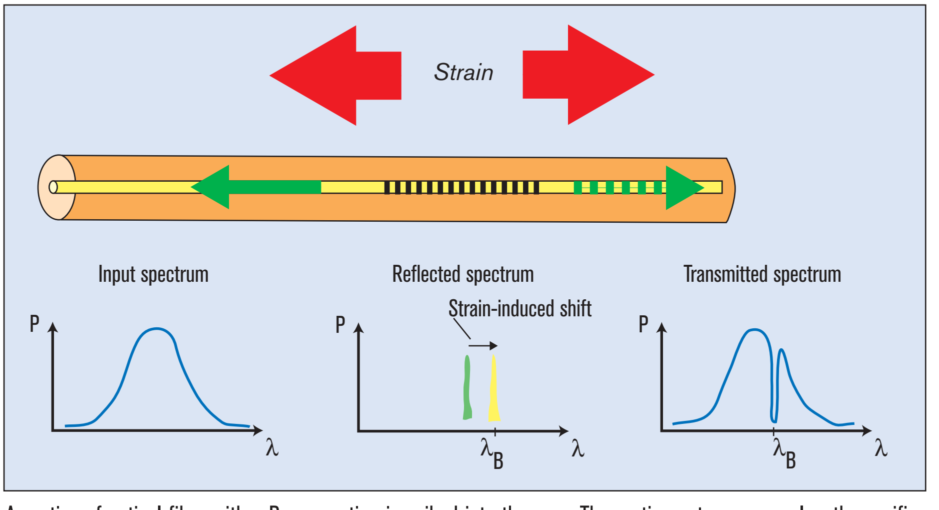
Total internal reflection allows light to travel through the core of an optical fiber by bouncing off the cladding. To be refracted it must enter the cladding, as illustrated. As a small amount of the light travels in the cladding, the optical clarity of the cladding is critically important.

- the third part of the system is the photodetector in the receiver, which takes the optical signal from the fiber and converts it into an electrical signal for transmission through the non-optical portions of a network. Again, in oilfield sensing applications this resides in the surface instrumentation package

How do DTS measure temperature distribution?

A DTS measures the temperature distribution along an optical fibre. A short pulse from a laser is launched into the fiber. As the pulse propagates along the fibre it will be attenuated, or weakened, by absorption and scattering. The scattered light will be sent out in all directions. Some will be scattered backward within the fiber's core and this radiation will propagate back to the transmitter end where it can be detected.

The scattered light has several spectral components. Most of it consists of Rayleigh scattered light, which is often used for optical fiber attenuation measurements. The wavelength of the Rayleigh light is the same as for the launched laser light. Another process where light is scattered at slightly different wavelengths than the launched



A section of optical fiber with a Bragg grating inscribed into the core. The grating acts as a wavelength specific reflector of light. When the grating is subject to strain, the reflected wavelength shifts in a linear manner. Thus, the grating can be viewed as an optical strain gauge.

wavelength is Raman scattering, which is temperature dependent. The time delay between launch and return gives the location from which the scatter signal is coming. By measuring the strength of the Raman scattered signal as a function of delay, it is possible to determine the temperature at any point along the fiber.

What are Bragg Sensors and how are they used in downhole monitoring?

Bragg gratings are intrinsic sensor elements that can be written into the core of an optical fiber by an ultraviolet photo-inscription process. The grating is a periodic modulation of the refractive index of a small section of the core of the fiber.

If broadband light is directed down the fiber, the grating produces a narrow-band reflection whose wavelength is proportional to the modulation periodicity of the refractive index. The remainder of the light passes through the grating and may be used to interrogate other sensors written at different wavelengths. This characteristic makes Bragg gratings an important component for permanent optical monitoring because it serves as the basis for wavelength division multiplexing (WDM). This is the ability to carry multiple channels of data down a single fiber simultaneously. For the purposes of reservoir management, WDM enables multiple optical sensors to be deployed downhole on a single fiber.

When a Bragg grating is subjected to strain, the reflected wavelength shifts in a manner directly proportional to the strain in the grating. Thus, the grating is an optical strain gauge. Through appropriate packaging to convert the desired measurand to strain of the grating and with suitable calibration, Bragg gratings can be used to measure a wide range of physical parameters in the wellbore.

Bragg grating-based sensors have many advantages for in-well monitoring applications including:

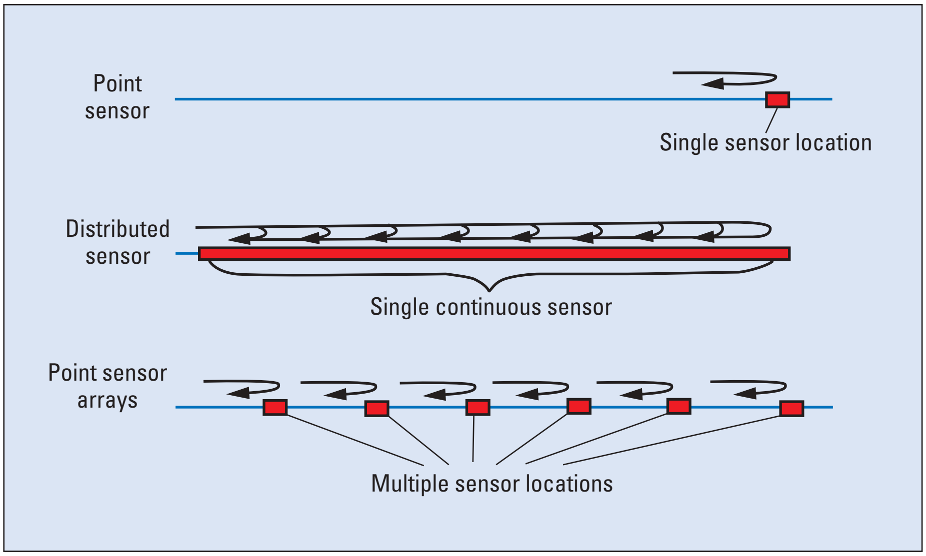
- intrinsic sensor element;
- no moving parts;
- electrically passive;
- high sensitivity and wide operating range;
- multi-point sensing capabilities;
- low physical profile;
- chemical and corrosion resistance
- multi-parameter sensing; and
- leverages off telecommunications technologies.

Bragg grating sensors have been developed to measure a wide variety of parameters, including temperature, pressure, vibration, acoustics and displacement.

What optical sensing architectures are possible?

Fiber optic sensing systems can be implemented in single-point, multi-point, and continuous distributed sensing configurations. In a continuous distributed configuration the entire optical fiber is used as a sensor. The result is a log of the measured quantity along the length of the wellbore. To date, continuous configurations in wells have been used primarily for DTS, although distributed strain measurements are also possible. The other two sensing configurations, single-point and multi-point, involve measurements at discrete locations along the length of the optic fiber in the wellbore. These offer a much broader range of measured parameters than continuous configurations. They also provide higher accuracy, precision and spatial resolution.

Today, in-well fiber-optic sensing systems leverage the technology advances in photonics by industries such as telecommunications, medical and military. There is a wide range of sensing capabilities including discrete pressure, temperature, multiphase flow, seismic and also distributed temperature monitoring. The level of technological development seen to date will continue and further advances will lead to an even greater number of sensor types and system architectures becoming available. This will be a major factor in gaining the level of production and reservoir management ability required to exploit today's complex and challenging oilfield developments. ●



Configuration modes for permanent in-well, optical sensing systems.