Specialty Optical Fibers for Harsh Environments

BY DR. SAEED REHMAN, FIBERTRONIX AB,
AND DR. LARS NORIN, ACREO AB

Fiber optic sensing is one of the fastest developing technologies today, and fiber sensors have seen increased acceptance and widespread use in many commercial applications. These include structural sensing, smart structures and civil engineering; aerospace and security; marine, oil and gas; and health monitoring. The most common functions are temperature and strain/stress sensing, but a variety of other parameters, such as pressure, magnetic field, voltage and chemical species, also can be measured. The main component of these sensors is the optical fiber, acting as the sensing element.

A key application currently benefiting from this technology is oil and gas exploration. Data published by the US Department of Energy indicates that approximately two-thirds of the oil discovered in the US remains in the ground after the primary and secondary recovery operations have been completed. This results from the lack of robust instrumentation to accurately and reliably monitor processes in the harsh downhole environments.

Optical fiber-based sensing instrumentation has been demonstrated to be especially attractive for the measurement of a wide variety of physical and chemical parameters because of such inherent advantages as immunity to electromagnetic interference, avoidance of ground loops, ability to respond to a wide variety of measurands, avoidance of electric sparks, resistance to harsh environments, remote operation, multiplexing capability, and ease of integration into large-scale fiber networking and communication systems. The basic component of these devices is the optical fiber that acts as the sensor.

Stress and strain

We define a "harsh environment" for these optical fibers as follows: temperatures above 100 °C; atmospheres containing water (liquid or vapor), hydrogen or other gases that destroy the fiberglass or coating; mechanical stress imposed by tight bend configurations or linear movements; and ionizing radiation such as UV, x-ray or gamma. Commercially available sensors for measurement of pressure, temperature and liquid flow exhibit shortened lifetimes in these conditions, which are characterized by high pressures, temperatures up to 250 °C and chemically reactive fluids. In many of these conditions, the glass will not be directly exposed, but the coating will play the key role in protecting the glass. If the coating survives, the glass will continue to perform.

Optical fiberglass has a mechanical strength that is inherently better than that of steel or copper. The primary role of the coating is to protect the glass surface from abrasion, which would drastically reduce the mechanical strength of the fiber. To maintain this protection, the coating must not burn off, disintegrate or peel during operation in harsh environments. Furthermore, the coating should not change its dimensions or lose flexibility, thus causing optical attenuation because of microbends.

It is important for systems designers or fiber end users to select the most suitable

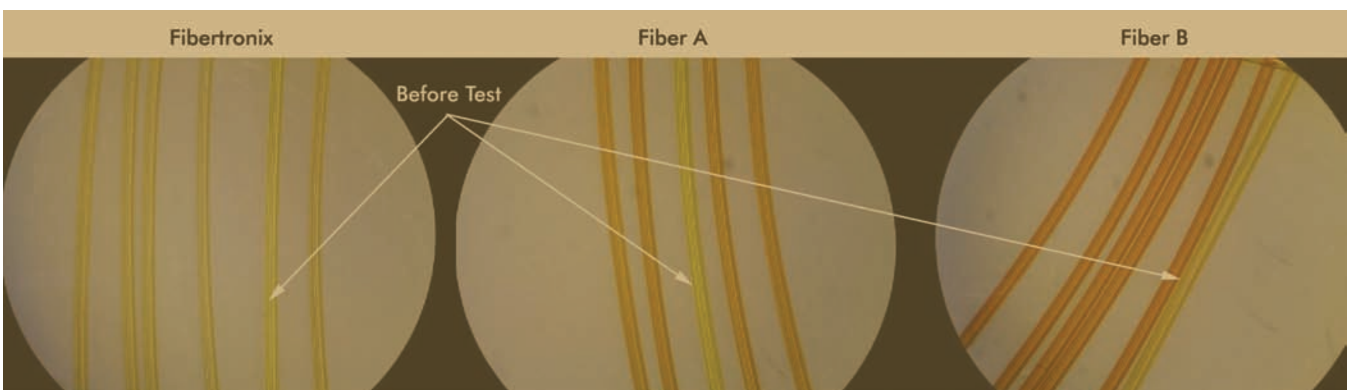

Figure 1. Polyimide fiber exposure to 180 °C and 1034 bar pressure. The fibers marked "before test" are not exposed.

Reprinted from the October 2010 issue of PHOTONICS SPECTRA © Laurin Publishing

coating for their specific operating conditions. For example, standard telecom acrylates are rated only up to 85 °C, but special coatings such as polyimide, silicone and high-temperature acrylate are available that are suitable for higher temperatures. The high-temperature acrylate, which can withstand up to 150 °C, is a good alternative at moderate temperatures. Silicone, although suitable for temperatures up to 200 °C, sometimes is not as popular with systems engineers due to its outgassing. Polyimide, on the other hand, is a robust coating for high pressure and temperature up to 300 °C.

Coating that sticks

In a high-pressure ambient, some polyimide coatings may degrade and peel off from the glass, thus exposing the surface. One solution is to use a coating that adheres strongly to glass, such as the polyimide coating from Fibertronix, which can sustain high pressures due to this quality. Figure 1 shows the degradation of different fibers under high-pressure exposures.

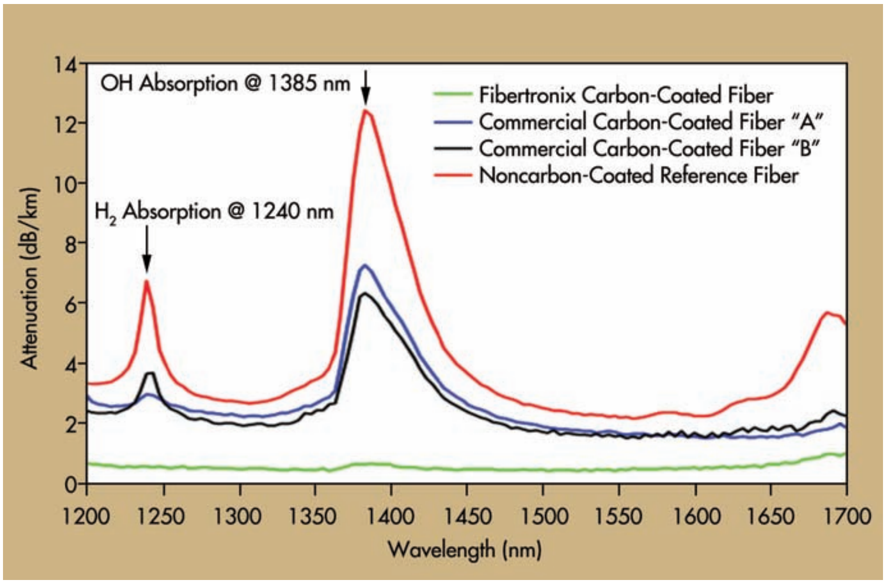

Figure 2. Spectral attenuation for four types of fiber after exposure to 1 atm H_2 at T = 170 °C.

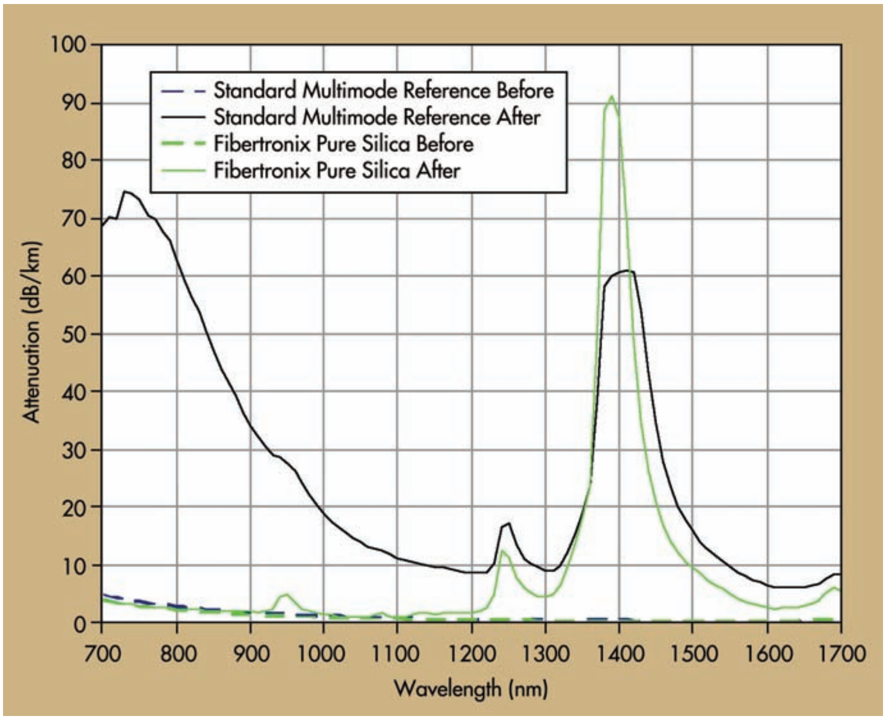

Figure 3. Spectral attenuation for a conventional (germanium-doped) multimode fiber before (dashed) and after (solid) three weeks of exposure to 1 atm H_2 at T = 250 °C.

Besides serving as a mechanically protective layer, the coating is essential also for defending the glass surface from moisture and tight bends. Water adsorbed on the glass surface enhances crack propagation upon mechanical stress, which eventually leads to fiber breakage (fatigue). Special hermetic coatings such as carbon can block water permeation and reduce such fatigue, increasing the lifetime of the system. These hermetic coatings also can be optimized to block diffusion of hydrogen into the fiber.

It is well known that hydrogen readily diffuses into the core of a standard fiber and creates a strong increase in optical background loss, a typical problem in downhole oil and gas fiber sensor applications. Only by employing hermetically coated fibers has it become practically possible to exploit fiber optic sensors for applications in hydrogen-rich environments. Figure 3 illustrates the effective blocking of H_2 by carbon-coated fibers. The Fibertronix carbon coating effectively protects the fiber from these losses when it is exposed to hydrogen-rich environments at high temperatures.

However, in many applications, it is not desirable to use carbon coating, and alternative solutions are required to protect the glass from the attack of the hazardous gases. One possible solution is to modify the glass composition of the core.

Pure silica core

A different approach to mitigating H_2-related loss is to use a fiberglass material less prone to chemical reaction. By using a fiber with a pure-silica core (PSC), the H_2-induced loss is much less severe. Hydrogen will still diffuse into the pure silica to form molecular absorption at 1240 nm, and Si-OH absorption occurs at 1385 nm. The important difference, however, is that conventional germanium-doped fibers also display a strong induced attenuation for shorter wavelengths due to reaction with germanium sites, whereas the PSC fiber remains practically unaffected in this region. Hence, PSC fibers will be perfectly suited in distributed temperature sensor applications in harsh environments, since they frequently use a 1064-nm signal wavelength.

Ionizing radiation is harsh on the fiber, as it induces optical losses that limit the lifetime of fiber optic devices, for instance in the nuclear industry. This induced loss is dependent on the composition of the glass. Not only do PSC fibers sustain ambients with hydrogen and heat, but also they are less prone to radiation-induced losses. Another approach to obtaining radiation hardness is adding certain dopants to the fiber core glass. Cerium has been demonstrated to mitigate gamma ray-induced darkening by annihilation of color centers in the silica. Unfortunately, prolonged exposure to radiation also leads to deterioration of most polymer coatings. This problem may be circumvented by applying a metal coating.

Radiation hardness

A number of added functionalities can be obtained by replacing the polymer coating with metal. Unlike polymers, metals do not outgas in vacuum, they do not ignite, and they lend themselves to mounting by soldering. When it comes to harsh environments, metal-coated fibers also exhibit many attractive features. Like carbon-coated ones, metal-coated fibers are protected against ingression of water and hydrogen. Furthermore, metal coatings provide unsurpassed heat resistance; fibers coated with aluminum or copper, for example, may sustain temperatures well above 400 °C.

The coating process typically involves application from a melt during fiber drawing, which adds a lot of complexity to the manufacturing process. Metal-coated fibers commonly show high microbend losses, mainly arising from the production process due to the mismatch in the thermal expansion coefficients of silica and the metal. Nevertheless, metal-coated fibers are still justified as a robust solution to fiber optic operation in harsh environments, particularly at extreme temperatures where other coatings such as carbon/polymer cannot survive.

The significant advantages that fiber optic sensors hold over more conventional ones are their distributed sensing and performance in extremely harsh environments. However, only in recent years has this technology matured sufficiently to find real field applications and to see steady growth in both standard and niche applications. As the expansion of fiber optic sensor applications continues, the affect on several business sectors will be significant.

Meet the authors

Saeed Rehman is vice president of business development at Fibertronix AB, Hudiksvall, Sweden; e-mail: saeed@fibertronix.com; Lars Norin is senior scientist at Acreo Fiberlab, also in Hudiksvall; e-mail: lars.norin@acreo.se.