

# Advanced Optical Fibers for Geophysical Sensing Applications

**Paul E. Sanders**

*QOREX LLC  
101 Hammer Mill Road  
Rocky Hill, CT 06067  
[pauls@qorexllc.com](mailto:pauls@qorexllc.com)*

**Abstract:** Growth in fiber optic sensing in the geophysical sector, predominantly in downhole oil and gas applications, has spurred refinement of optical fibers primarily to endure the harsh high temperature, hydrogen-rich well environment. This paper reviews advanced sensing fiber design and field performance under these conditions, as well as some new fiber and waveguide designs for enhanced sensor functionality and performance.

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## 1. Introduction

The range of geophysical applications and general use of fiber optic sensors has accelerated since the commercial introduction of permanently installed fiber optic systems in the demanding offshore sector of the oil and gas industry. Fiber optic sensors were first introduced as an upgrade technology over legacy electronic sensors for high reliability at elevated temperature, leveraging a passive, silica-based optical fiber based downhole sensing section connected at surface to an active data acquisition module. Once field-proven, several major oilfield services companies soon introduced fiber optics sensors in their well services and completions products. Being offered in the traditional supply chain has spurred fiber optic sensor commercial growth and adoption by the mainstream of the market, today serving all regions and most operators. The initial motivation for reliability at high temperature has since been replaced by the unique ability of some fiber optic sensors to be configured in a fully distributed sensing architecture. This allows full wellbore profiling in real time to enable greater insight into flow of well fluids over time, and reservoir response to production operations- critical information to enhance overall asset management, production efficiencies, and ultimate recovery.

With well depths sometimes exceeding 6km and a nominal geothermal gradient of 30°C/km, it is not uncommon for well temperatures to exceed 180°C and even higher. Besides high temperature, downhole oil and gas application of fiber optics presents a harsh hydrogen environment- the product of galvanic reaction of well fluids and metal completion parts installed in the well. Hydrogen liberation, diffusion and subsequent reaction with the installed fiber can cause significant hydrogen-induced spectral attenuation that leads to measurement error and catastrophic optical failure. Fiber optic sensing systems that were commercially introduced in the late '90s likewise utilized a first generation of geophysical fiber and hermetic cable designs that were qualified for high temperature, hydrogen environments for wells operating up to 150°C, a rating that can address the bulk of the target offshore market. Since then, refinements in sensing fibers have been made that improve upon these initial designs, primarily to upgrade their rating and subsequent use in high temperature, high pressure (HTHP) offshore wells operating up to 185°C. Over the past few years however, high commodity pricing and new technology has unleashed thermal recovery of the vast heavy oil and oilsands resource, that typically involve steam flood processes with well temperatures in excess of 300°C. This has led to the development of specialized fibers that endure these aggressive thermal and hydrogen well conditions. This paper will present the range of geophysical fibers specific to these application segments, reviewing design approaches for long-term mechanical and optical reliability under these harsh conditions. Advanced waveguide designs that improve sensor performance or functionality will also be presented.

## 2. Mechanical Reliability

While supplied as specialty fibers, geophysical fibers are produced and tested using conventional telecommunications-grade fiber materials, processes and standards. As such, they follow much of the same fundamental strength and reliability characteristics, but depart from their telecom counterpart in the use of higher temperature fiber coatings. These include high temperature acrylates rated to 135°C, silicone/fluoro-polymer to 185°C, and polyimide to 300°C. While the former materials exhibit good fiber coating characteristics to closely follow telecom fiber mechanical behavior, the latter involves a more complex thermal process, and as a consequence, inconsistent coating quality and degree of thermal cure among suppliers. Subsequent variability in fiber mechanical and thermal performance of these fibers requires greater test and characterization, which benefits in

use of alternate analysis such as thermo-gravimetric analysis [1] to screen fiber for reliability and lifetime at application temperatures above 250°C. Field performance of each of these high temperature fibers is encouraging with low incidence if any mechanical field failures. Of note is the use of carbon-coated fibers in permanently-installed ocean bottom seismic systems. After significant evaluation, this coating is used almost exclusively in these systems to impart extended operating lifetime, and in some cases act as a hermetic barrier against hydrogen ingress.

### **3. Optical Reliability**

Initial geophysical fibers utilize conventional commodity fiber waveguide and glass. In particular the use of ITU-T G.651 graded index multimode fiber is standard in Raman-type distributed temperature sensors (DTS)- the most prevalent sensor in the oil and gas industry. Pure silica core fibers, in particular Sumitomo “Z” type fiber, are also in service in many offshore optical point sensors for resistance to hydrogen-induced attenuation. This is addressed by some systems suppliers through use of hermetic fiber coatings and cable structures. Carbon hermetic fiber coatings have tested suitable for use up to 110°C. Use of specialized metal hermetic cable materials can slow hydrogen diffusion at design operating temperatures up to 200°C, beyond that however there are no practical hermetic materials, subjecting the fiber to hydrogen which is ubiquitous in any well environment. Hydrogen diffusion in optical fiber manifests into both transient and permanent attenuation in which the magnitude of latter is dominant and highly dependent on the glass composition of the optical fiber itself. While transient losses are reversible, the absorption of dissolved hydrogen in the glass, permanent losses are irreversible, the product of chemical reactions between hydrogen with glass precursor defects that form light absorbing species. This can lead to significant spectral attenuation and optical failure. Hydrogen-induced attenuation is particularly problematic in Raman DTS that is subject to measurement error due to differential fiber attenuation, and has been the primary failure mode for these sensors in thermal recovery applications that operate at temperatures above where hermetic cables are effective [2]. Recent advancements in pure silica core sensing fibers that minimize the onset of hydrogen reactions, and use of new measurement protocols to compensate measurement error in Raman DTS systems due to transient hydrogen effects have successfully addressed this problem [3]. Further improvement in hydrogen performance of these fibers can be achieved by deuterium treatment of the fiber [4] to react any residual defects to form deuterated species with absorption that are out of band e.g. SiOD (1900nm). The full set of hydrogen mitigation strategies- hermetic fiber coatings, cable designs, and use of pure silica core fibers, provide practical solutions to effectively harden downhole optical fibers to a full range of well conditions up to 300°C.

### **4. Enhanced Functionality**

The use of G.651 fiber is attractive to impart a high Raman cross-section i.e. intensity of return backscatter signals that drives signal averaging time and sensor measurement update rate. Furthermore the high bandwidth relative to step-index fiber allows finer spatial resolution for time-delay type distributed sensors. Unfortunately this fiber is among the most sensitive to hydrogen, and can only be used reliably in lower temperature applications within the effective range of hermetic materials. Recently, new hydrogen-tolerant fibers with bandwidth >300MHz-km have been introduced. While their design is proprietary, hydrogen performance tests show these fibers with comparable performance to pure silica core fibers. This allows for greater spatial resolution Raman DTS performance in high temperature applications such as steam flood, where the improved resolution can detect phase fronts over long intervals. Other advanced functionality fibers include dual core sensing fibers with different strain and temperature response of collocated fiber Bragg gratings in the fiber. Use of alternate waveguide structures is also used to promote differential acoustic propagation in the fiber to discriminate strain from temperature in Brillouin sensors. An example is the use of dispersion-shifted fiber with structural features that promotes Brillouin frequency spectra with multiple peaks having different response to strain and temperature that can be analyzed to enable simultaneous distributed temperature and strain sensing. These and other advanced fibers will be presented.

[1] Stolov et al. “Thermal Stability of Specialty Optical Fibers”, Journ. Lightw. Tech. Vol. 26, No. 20, 2008

[2] J. Kaura et al. “ Successful Field Application In Continuous DTS Monitoring Under Harsh Environment of SAGD Wells Using Improved Optical Fiber Technology”, Society of Petroleum Engineers, Paper SPE-117206 2008

[3] P. Sanders et al. “Recent Developments in Fiber Optic Sensor technology For High Temperature Well Monitoring” Proceeding Geothermal Resource Council Annual Meeting, Reno 2009

[4] E. Lindholm “Advancements in High Temperature Optical Fiber Mechanical Reliability and Hydrogen Performance” Society of Petroleum Engineering Workshop on Distributed Temperature Sensors, Austin 2009