

Novel Optical Fiber Design for Hydrogen-rich Harsh Environment

Imtiaz Majid, Kanxian Wei, Gary Drenzek, Chih-Hao Wang, Abdel Soufiane

Abstract

We report on a new class of novel optical fiber structures, designed for use in harsh environments typical of oil and gas applications. Specifically, we focus on fiber designs that alleviate the effects of hydrogen ingress and its associated darkening of optical fibers in harsh environments. We demonstrate, theoretically, how a carbon-coated optical fiber structure, consisting of an array of randomly or systematically placed voids running along the length of the fiber, can lead to significantly reduced hydrogen ingress effects. The array of voids can be of arbitrarily varying shapes and sizes along the length of the fiber.

We derive an equation describing the increase in the fiber lifetime as a function of the average cross-sectional fraction of voids in the fiber. Fiber darkening effects are predicted to decrease by factors of as much as $\times 10$, for moderately low fraction of voids in the fiber cross-section. Theoretical predictions are confirmed experimentally by performing ingress tests in a hydrogen test chamber with online monitoring capability, simulating downhole temperatures and pressures. Additional geometric factors, such as fiber diameter, that may also be optimized to further improve the hydrogen ingress resistance of fibers are discussed; in this vein, a new larger form-factor fiber, different from the standard 125 μm fiber, is proposed. Finally, the lifetime predictions greater than 5-10 years obtained for such void-filled optical fibers in typical downhole conditions make them extremely attractive candidates for use in oil and gas applications such as well monitoring and logging.

Keywords: Hermetic, optical fiber, harsh environment, hydrogen-ingress, fiber darkening, distributed temperature sensing

Introduction

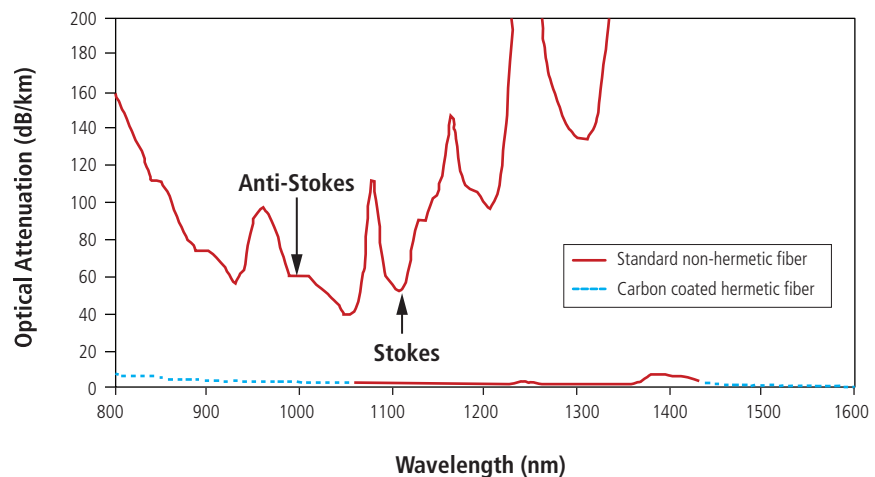
Optical fibers, with some form of protective coating on the glass surface, have been used in downhole applications for a number of years by the oil and gas¹ industry. In these applications, the optical fiber is employed either as a distributed or point sensor, or as a data communication highway in geophysical and geothermal wells. While typical downhole applications are ~2-4 kilometers in depth, deeper wells can approach 7 kilometers deep. The use of optical fibers to either retrieve data at high bandwidths over long distances, not available via copper transmission lines, or to obtain detailed distributed or point, temperature, pressure and flow measurements along the well bore is essential for the optimization of oil production in "Intelligent Wells." While the benefits of using optical technology over traditional electronic techniques have been demonstrated, the widespread use of optical fiber in downhole applications is just beginning to occur.

Although many fiber optic based measurement techniques have been demonstrated in downhole applications, one of the most commonly used and widely deployed systems in oil wells is a Distributed Temperature Sensing (DTS)^{4,2} unit; these systems use Raman backscattering in glass to provide a continuous temperature profile along the length of a fiber optic cable. The principle of DTS operation is based on Optical Time Domain Reflectometry (OTDR) using the intensity of Raman backscattering as the temperature detection feature. In this technique, the launch-to-detection time defines the position along the sensing fiber and the reflected Anti-Stokes Raman signal intensity defines the temperature level. The Raman Anti-Stokes band is used for temperature sensing as it is very sensitive to temperature variations. The Stokes band being less sensitive to temperature is typically used for loss calibration. Optical fibers have been successfully deployed and used in DTS systems throughout the world.

Typical multimode DTS systems work around the 1060 nm band. This spectral region benefits from the availability of high power lasers and the low attenuation of optical fibers. As mentioned above, for DTS techniques using optical fibers to work effectively in predicting the temperature profile of long wells, it is essential that the spectra in the very weak Stokes and Anti-Stokes lines region remain unchanged by extraneous effects. This allows the detection of intrinsic changes in their spectral characteristics due to local temperature variations.

There are several major impediments to the widespread use of optical fiber technology in a downhole environment. First, it is relatively new, compared to what has been used for the majority of the last century, e.g. electronics; and there is the usual concern associated with introducing new technology in a well-established, highly cost and reliability conscious industry. Secondly, the characteristics of the fiber regarding handling (deployment, connectorization, splicing etc.) and performance are not fully understood. Of the former, one can say that significant efforts need to be made to standardize handling issues currently faced by well completion groups involved in such deployment. However, this does not appear to be a fundamental operational barrier that cannot be overcome. Finally, and most importantly for the purposes of this paper, the down hole environment is fairly harsh in that it is a high temperature, high pressure, highly corrosive environment, containing free molecular hydrogen. The free hydrogen diffuses with relative ease through the layers of metal/polymer/casing to the optical fiber where it can react with the different dopants in the core of the waveguide and significantly alter the spectral transmission. Figure 1 shows the attenuation spectrum of an optical fiber before and after it is exposed to hydrogen. Also shown in Figure 1 are the positions of the Stokes and Anti-Stokes lines. Figure 1 clearly illustrates how the background at the position of the Stokes (S) and Anti-Stokes (AS) lines changes as a function of hydrogen ingress. The level of change at the S-AS lines indicated in Figure 1 would be disastrous for any DTS system attempting to extract meaningful temperature profiles.

Figure 1: Effect of Hydrogen Ingression on Multimode Optical Fibers at 200°C, 1500 psi of H₂ for 17 hours, the typical DTS lines (Stokes and Anti-Stokes) of interest ~1064 nm are indicated.



To evaluate hydrogen ingress in optical fibers, it is first necessary to identify parameters that are suitable for use in characterizing the in-diffusion of hydrogen into the fiber; this is particularly challenging since hydrogen reacts with the glass and gives rise to absorption peaks and overtones that considerably complicate the spectral landscape. Furthermore, the reaction rates and the growth rates of different peaks are strong functions of temperature, since the H₂ in-diffusion rate and its reaction rate with different dopants in the optical fiber both depend strongly on temperature.

In this study, we will use a parameter called “permeation time constant” to quantify the amount of hydrogen that diffuses through the protective coating applied to the glass surface of the fiber; as well, we characterize the temperature dependence of this parameter, which allows the prediction of hydrogen ingress characteristics of the protective coating at any temperature. The permeation time constant describes the rate at which the concentration of hydrogen in the fiber increases, and ultimately reaches equilibrium with the environment that the fiber is immersed in.

Therefore, in this paper we will focus primarily on fiber designs that reduce the amount of hydrogen that ingresses into the optical fiber. Other characteristics of the fiber design that play a role in determining the effects of hydrogen on the spectral attenuation relate to core dopants (Ge, P).

Carbon Coated Optical Fibers and the Permeation Time Constant

The traditional method of providing protection to optical fibers in harsh environments has been the application of an impervious coating on the surface of the glass. Many different coatings have been explored, e.g. metals³ ceramics^{4,5} and carbon^{6,7}. Metals tend to form polycrystalline structures where the grain boundaries act as short circuit diffusion paths and can themselves get rapidly corroded in harsh environments; additionally even soft metals such as tin and aluminum tend to induce micro-bending losses.

Ceramic coatings such as silicon nitride or silicon carbide have also been used, and have demonstrated to be effective in providing resistance to water at elevated temperatures and pressures. However for these coatings, generally the mean strength is significantly below the value for standard polymer coated glass fibers, and as in metals, due to the high modulus of these materials the coatings tend to give rise to significant micro-bending losses. Hence, neither ceramic nor metal coatings can fulfill the requirements for strength, hermeticity and bend loss all in the same fiber. In addition, producing long continuous lengths of these fiber types has proven problematic due to processing complexity.

Carbon coatings on the other hand appear to be the most attractive in providing solutions to all the above mentioned problems for temperatures in excess of 100°C; at these temperatures e.g., saturation lifetimes with respect to hydrogen ingress are on the order of years; micro-bending is minimal and mean strength while on average still below the optimal values obtained for polymer coated fibers, can be slightly improved with improved process/roughness control during the deposition of carbon. Carbon coated optical fibers have been manufactured in the past⁷; and the carbon permeability to hydrogen extensively studied⁸. The time dependence of the concentration of hydrogen in the glass fiber is given by Le Maire et al.⁸

$$\text{Equation 1} \quad \frac{H_2 \text{ Conc}(t, T)}{H_2 \text{ Conc}(\infty, T)} = \left[1 - \exp\left(\frac{-(t-\tau_i)}{\tau_f}\right) \right]$$

Where τ_i and τ_f are parameters related to materials properties of the carbon fiber. In particular $\tau_f \sim r\delta/2DK_{cs}$. Where "r" is the radius of the fiber, "δ" is the thickness of the carbon coating, D and K_{cs} , respectively are the diffusivity and solubility coefficients of hydrogen in the carbon relative to silica. Since the concentration of hydrogen in the glass is difficult to measure directly, we estimate the left hand side (LHS) of equation (1) by measuring the change in attenuation at the molecular hydrogen peak at 1.24 μm. The magnitude of this peak is directly proportional to the concentration of molecular hydrogen in the core of the fiber. Equation 1 then becomes

$$\text{Equation 2} \quad \frac{\Delta\alpha_{1.24}(t, T)}{\Delta\alpha_{1.24}(\infty, T) \times P_{H_2}} = \left[1 - \exp\left(\frac{-(t-\tau_i)}{\tau_f}\right) \right]$$

Where $\Delta\alpha_{1.24}(t, T)$ is the change in attenuation (at 1.24 μm) after the fiber has been exposed to hydrogen environment for time t at temperature T; $\Delta\alpha_{1.24}(\infty, T)$ is the change (per unit hydrogen pressure) in attenuation when equilibrium has been reached between the fiber and the environment; and P_{H_2} is the hydrogen partial pressure. τ_i and τ_f are the time constants for initial lag (before any increase in attenuation is observed) and the rate at which the attenuation increases at any given temperature T. Also for relatively thin coatings, τ_i is generally much less than τ_f . For relatively short times, Equation 1 becomes

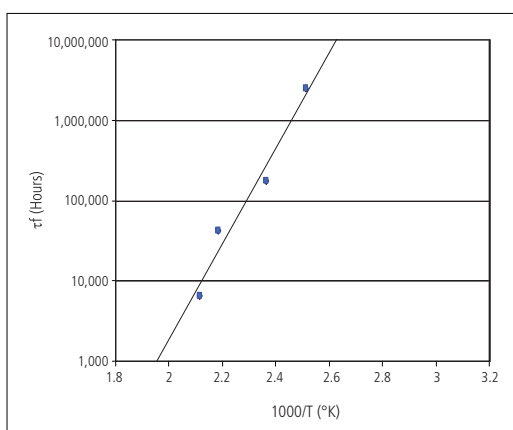
$$\text{Equation 3} \quad \frac{\Delta\alpha_{1.24}(t, T)}{\Delta\alpha_{1.24}(\infty, T) \times P_{H_2}} = \left[\frac{t}{\tau_f} \right]$$

A plot of the LHS of Equation 2 vs. time "t" should yield a line with slope $1/\tau_f$. τ_i and τ_f contain all the information of interest regarding the permeation characteristics of the carbon coating. Larger values of τ_f imply a more resistant coating, and maximizing its magnitude has been the goal of many researchers⁸. Most studies to date that have tried to optimize the value of τ_f have focused on the carbon application conditions and the selection of the carbon precursor^{9,10}.

One of the key properties of the permeation time constant is that it describes only the hydrogen permeation characteristics of the protective coating on the surface of the glass fiber, independent of the properties of the glass. This allows us to separate out the resistance

to H_2 of the protective layer from that of the glass. Note that this is only true for relatively low temperatures since the molecular hydrogen peak at $1.24 \mu m$ is affected by an OH overtone, which occurs at $1.27 \mu m$. The magnitude of this peak is however quite small except at high hydrogen pressures or high temperatures, when the OH absorption is substantial. Additionally, this information allows the design optimization of the glass and carbon layer independently. The permeation time constant has an Arrhenius temperature dependence, $\sim A \exp(-B/kT)$; the parameters of the Arrhenius equation, A and B can be extracted from a plot of $\ln \tau_f$ vs. $1/kT$, as shown in Figure 2. Knowledge of τ_f value and its temperature dependence characterizes the carbon coating fully in terms of its hydrogen diffusion properties at any temperature. Therefore, qualitatively, large values of τ_f correspond to a slower rate of equilibration of H_2 in the optical fiber, and a highly hermetic optical fiber will have a large value of τ_f .

Figure 2: Temperature Dependence of the permeation time constant τ_f .



Carbon Coated Optical Fibers with Voids in the Cladding

As discussed above, previous work relating to improving the performance of optical fibers in harsh environments has generally focused on modifying or optimizing the properties of the coating on the glass fiber surface. Researchers have met this goal with varying levels of success. For example, practical conditions in which suitable fibers can be employed may be restricted to temperatures below about $150^\circ C$, and even then, depending on the environment, the fibers may be able to withstand exposure only for relatively short periods of time. Here we address the problem of in-diffusing molecules in an optical fiber immersed in a harsh environment by modifying and optimizing the design of the glass component of the fiber itself, independently of the properties (or even the presence) of the hermetic coating. In particular, the approach consists of novel features in the structure of the glass fiber such that τ_f in Equation 2 is increased by as much as one or two orders of magnitude. The ensuing description utilizes hydrogen as an illustrative example of an ingressing species due to its small molecular size, which renders it a particularly troublesome diffusant, and its well-known undesirable effects on light transmission through a fiber. It should be understood, however, that these ideas are useful in mitigating the effects of virtually any ingressing species.

The proposed fiber design includes voids or gas trap lines (GTLs) that serve as sinks for ingressing molecules and can absorb a much higher concentration of ingressing molecules (in equilibrium) than the glass itself. Accordingly, in a first aspect, the proposed design provides an optical fiber with improved resistance to ingressing molecules, such as hydrogen molecules. The cladding of the fiber contains one or more voids that are spaced apart from the core to minimize interference with light traveling within the cladding and act as trapping sites for the ingressing molecules. The voids can extend longitudinally through the fiber. The voids can form a pattern of concentric rings to create a multidirectional barrier to ingressing molecules; alternatively, the voids may be disposed in a random pattern.

On the following page, we present a theoretical description of the effects of voids on the concentration of in-diffusing molecules (e.g. H_2) into a carbon coated optical fiber.

Consider now, the kinetics of hydrogen diffusion through a hermetic (e.g., carbon) barrier on the surface of the optical fiber with voids near the periphery (as shown in Figure 3). The carbon coating essentially slows down the kinetics of hydrogen diffusion into the optical fiber. As the hydrogen molecules penetrate the fiber, they rapidly equilibrate within the glass fiber and locally find the GTLs; in these traps the hydrogen molecules quickly attain equilibrium with the silica glass, so the GTLs “absorb” many times more hydrogen/unit volume than silica glass. Therefore, in a given period of time, if N hydrogen molecules entered through the hermetic barrier, in a conventional fiber they would disperse randomly throughout its cross-section A with a density N/A . For the GTL fiber of the present invention, by contrast, if the gas lines occupy an area A_1 of the cross-section of the fiber and contain N_1 ingressing molecules, and the rest of the fiber (silica glass) has a cross-sectional area A_2 and contains N_2 ingressing molecules, then the following relationships hold:

$$N = N_1 + N_2 \text{ and } A = A_1 + A_2$$

$$N_1/A_1 = K_{g-s} N_2/A_2$$

Where $1/K_{g-s}$ is the solubility of the ingressing molecules in the silica glass relative to the gas phase¹¹ and in the case of hydrogen has a value $K_{g-s} \sim 33$. Solving this set of equations for N_2/A_2 :

$$\text{Equation 4} \quad N_2/A_2 = N/(A - A_1 + K_{g-s} A_1) \equiv N/(\chi A)$$

If $A_1 = 0.10A$, with $K_{g-s} \sim 33$, then

$$N_2/A_2 = N/(4.2A)$$

Equation 4 can be re-written as:

$$\text{Equation 5} \quad {}^H_2 \text{Conc (void fraction} = A_1/A) = {}^H_2 \text{Conc (void fraction} = 0) / (1 - A_1/A + K_{g-s} A_1/A)$$

This means that, when the GTLs occupy 10% of the fiber cross-section, the concentration of ingressing molecules in the silica glass will be 4.2 times less than N/A (i.e., the equilibrium value in the absence of the GTLs); this occurs simply because the bulk of the ingressing molecules tend to reside in the GTLs. If the cross-sectional area of the GTLs is increased to 20-30%,

$$N_2/A_2 = N/(7.4A) \text{ for } A_1 = 0.20A, \text{ i.e. } \sim 7.4 \text{ fold decrease in } {}^H_2 \text{ conc. in glass}$$

$$= N/(10.6A) \text{ for } A_1 = 0.30A, \text{ i.e. } \sim 10.6 \text{ fold decrease in } {}^H_2 \text{ conc. in glass}$$

Even if the cross-sectional area occupied by the GTLs is only 3%, a two-fold decrease in H_2 concentration is observed:

$$N_2/A_2 = N/(1.96A) \text{ for } A_1 = 0.03$$

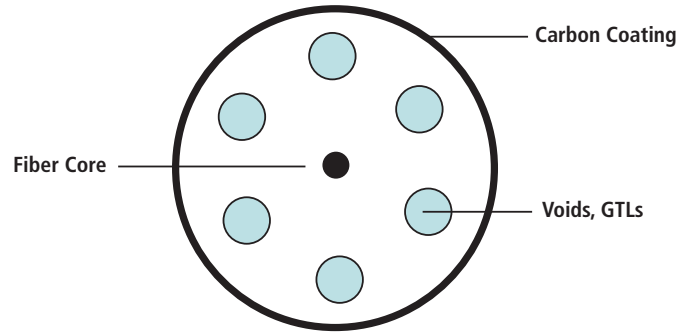
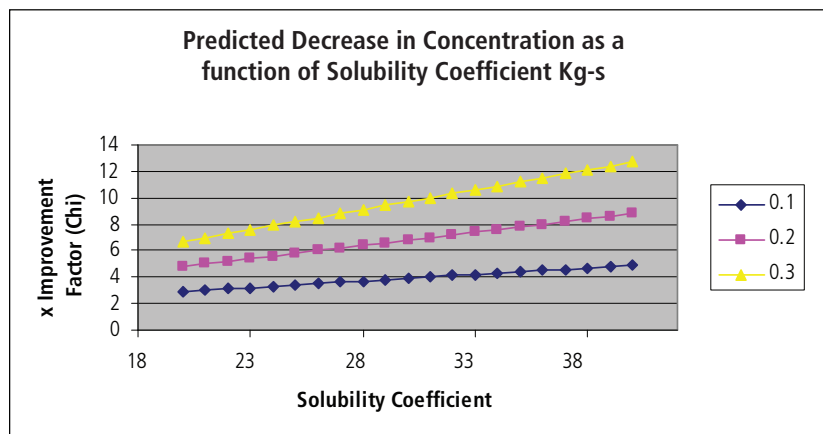


Figure 3: Schematic of Typical GTL Fiber with a carbon coating and a single-mode core.

In each of the cases above, the concentration of H_2 molecules in the glass has decreased by some factor χ ; since the attenuation of light in the fiber (Equation 2) at $1.24 \mu m$ is directly proportional to the concentration of H_2 molecules in the glass (this is not necessarily true at all other wavelengths nor at very high H_2 concentrations where the reaction rates of defects with H_2 may have different concentration dependencies), the cases above will give rise to a new effective τ_{eff} given by $\tau_{eff} = \tau_i \chi$. τ_{eff} is therefore the new time constant describing the concentration dependence of ingressing molecules on the optical fiber in the presence of a hermetic coating as well as the GTLs.

It is important to point out that increase in the fiber lifetime factor, defined by χ is strongly dependent on the value of the solubility coefficient; this is shown explicitly in Figure 4 where we have plotted the improvement factor as a function of the solubility parameter K_{g-s} for several different void fractions. Experimentally determined values of K_{g-s} appear to vary from ~ 27 to as high as 35 in the temperature range of interest¹¹.

Figure 4: Improvement factor vs. Solubility Coefficient, for area fraction of holes ranging from 0.1, 0.2 and 0.3.



Finally we note, from Equation 1, and its associated parameters that τ_i may also be increased by increasing the fiber diameter; in fact τ_i increases linearly with fiber diameter. This provides us with another dimension that may be optimized to reduce the concentration of hydrogen in the silica fiber.

Experimental Description

Preform and Fiber Processing

The optical fiber of this study was manufactured from a high purity glass preform using the draw tower method. Thin layers (a few hundred Angstroms thick) of carbon were applied to the surface of the drawn glass, and then the fiber was over-coated with a polyimide protective material to allow for high temperature testing. The quality of the carbon layer was monitored and exhibits great consistency over very long draw runs; this consistency was also confirmed by sampling different sections of the drawn fiber, and measuring the thickness of the carbon using a high resolution SEM and its roughness using AFM. The process parameters for the carbon application were adjusted to provide optimal hermeticity and consistency of the coating.

Manufacturing preforms that will contain voids when drawn into fiber is highly non-trivial, both at the preform manufacturing stage as well as the draw step. Preforms containing voids in the cladding were drawn into fiber at relatively low temperatures to preserve the voids. Prior to this the preform was manufactured in several steps whereby a MM 50/125 core rod was inserted into a larger diameter tube and supported inside this tube by three solid rods. The three rods were tacked onto both the core rod and the tube using heat. This preform was then cleaned and processed in standard fashion and polyimide carbon coated fiber was drawn from it. A cross-sectional image of the drawn fiber is shown in Figure 5a on the following page.

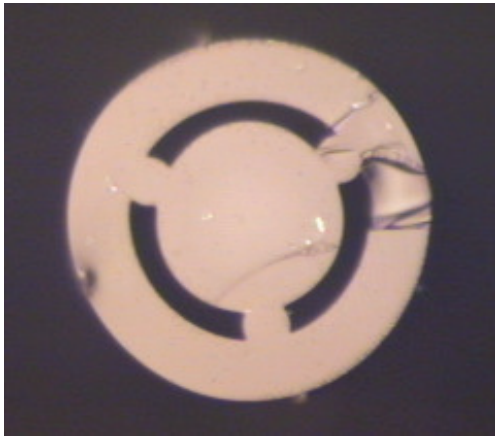


Figure 5a: MMF 50/125 GTL Fiber, with Voids

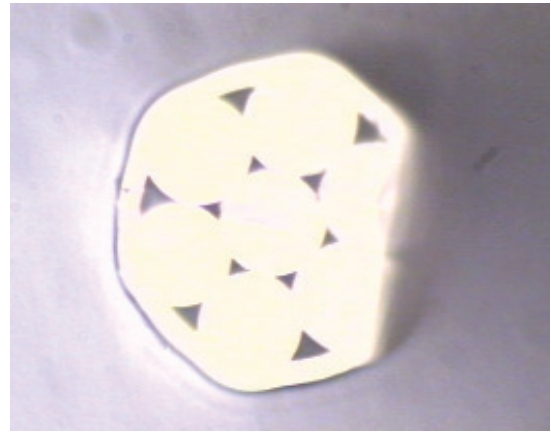


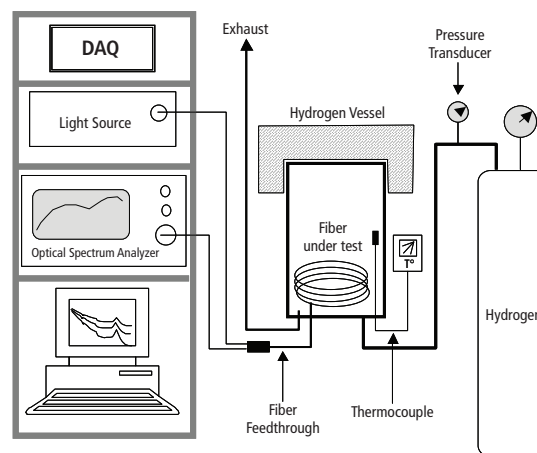
Figure 5b: Single-mode GTL Fiber, with Voids

Fibers with other void geometries have also been drawn. Figure 5b shows an example of another fiber with a single-mode core. Specific void geometries may be more suited to one waveguide design to minimize the effect on the optical characteristics of the fiber.

High Pressure Hydrogen Vessel and Online Testing

In order to simulate extremely harsh environments, a high pressure, high temperature, hydrogen setup was constructed allowing online measurements of hydrogen induced loss in the optical fiber. The H_2 setup is illustrated in Figure 6. The apparatus consists of a stainless steel chamber with high pressure optical fiber feed-throughs, a white light source, and an Optical Spectrum Analyzer (OSA). The data was collected electronically in real time in intervals of several minutes. The chamber is designed to be pressurized up to 2000 psi (of H_2) and heated to temperatures as high as 200°C.

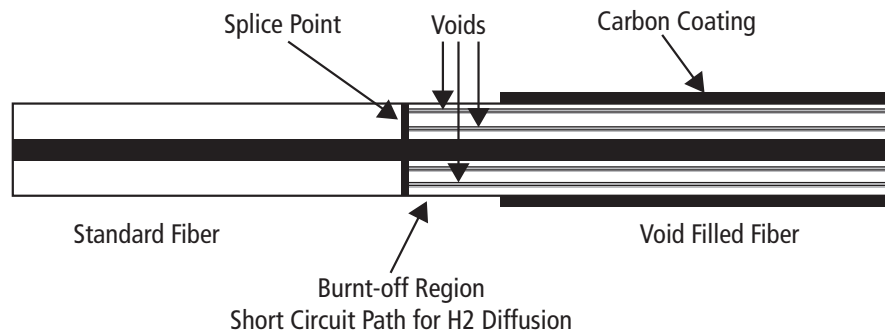
Figure 6: Online Hydrogen Testing Chamber and Accessories



As a general rule all hydrogen testing comparisons were done in a single test run. In order to compare the hydrogen ingress characteristics of the fiber with voids, we simultaneously test these fibers with ones whose core had been manufactured with an identical recipe but whose cladding does not contain voids. This allows us to eliminate variations in H_2 ingress results due to temperature and/or pressure fluctuations.

Testing fibers with voids in a hydrogen chamber is also not trivial. In particular since the feed-through fibers are standard (no voids) fibers, splicing these fibers to the fibers with long continuous voids is challenging, especially since the splicing of the region between the two fibers burns off some carbon from the test fiber (this is illustrated in Figure 7). This results in a “short-circuited” diffusion path for the hydrogen molecules into the test fiber. There are numerous ways to alleviate these effects such as the use of carbon coated capillaries that can be fused to the fibers on either side of the splice.

Figure 7: Splicing Carbon Coated GTL fiber to standard 125 μm fiber



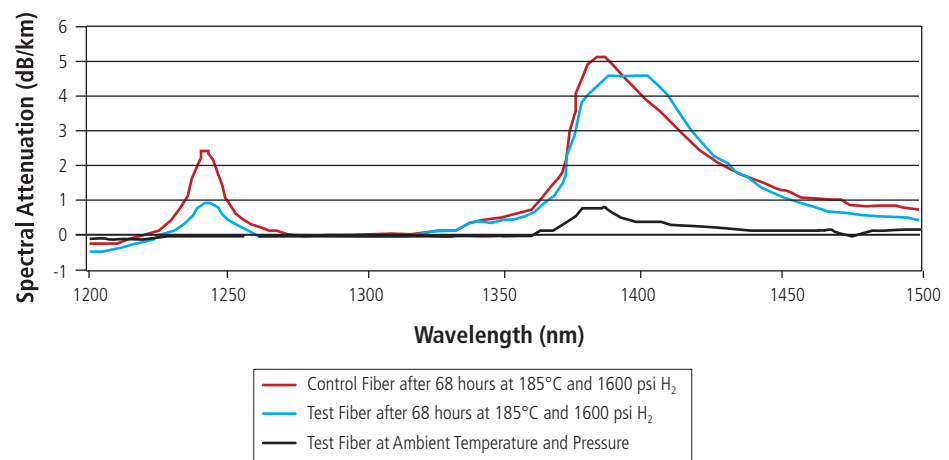
Experimental Results and Analysis of Hydrogen Ingression

Hydrogen Ingression Characteristics of SM Fibers with GTLs

A single-mode fiber with GTL's similar to the fiber shown in Figure 5b was manufactured by the techniques described above. The fraction of voids in the fiber cross-section for this fiber is approximately ~7-10%. A standard-design fiber without voids and with an identical core was also prepared. The optical spectra of the two fibers were taken before exposure to hydrogen. The test fibers were then placed in the H_2 chamber, and treated at 185°C and 1600 psi of hydrogen.

Another set of spectra was taken after ~70 hours exposure under these conditions and are shown in Figure 8. In this case it is clear that the peak at 1.24 μm shows that the fiber with voids has a smaller concentration of H_2 molecules in its core. Taking into account that there is an OH overtone contribution at 1.27 μm whose magnitude is approximately 1/15th the magnitude of the OH overtone at 1.38 μm , it is estimated experimentally that the fiber with voids has approximately 3.6 times lower concentration of H_2 molecules in the glass.

Figure 8: Change in Spectral Attenuation Curve for Single-mode Fibers after exposure to H_2 , for GTL fibers and standard SM fibers



Referring back to Equation 5 and substituting $A_1/A = 0.09$ (i.e. 9% of the cross-sectional area is filled with voids), we obtain the theoretical prediction, that the concentration of hydrogen in the void filled optical fiber is 3.88 times less than that of the standard (no voids) fiber. Our experimental finding of 3.6 times lower H_2 concentration is in excellent agreement with the theoretical prediction of 3.88.

It is interesting to note that in spite of the lower concentration of hydrogen in the void-filled fiber the growth of the OH peak at 1383 nm appears to be identical for both fibers. This is likely due to the relatively small number of defects (that bond to hydrogen) that exist in a single-mode fiber, so that the growth of the OH overtone is limited by the defect concentration and not by the concentration of hydrogen molecules inside the fiber.

Hydrogen Ingression Characteristics of MM 50/125 Graded Index Fibers with GTLs

Multimode fibers (50/125 or 62.5/125) are widely used in the oil and gas industry to obtain distributed temperature measurements in oil wells. Many of these systems use the 1064 nm region, with corresponding Stokes and Anti-Stokes lines at 1114 nm and 1014 nm to obtain distributed temperature measurements. To describe the benefits of the GTLs in reducing the effects of hydrogen ingress, we focus this study on the 1064 nm region and report on results relevant to some of the most widely used DTS systems.

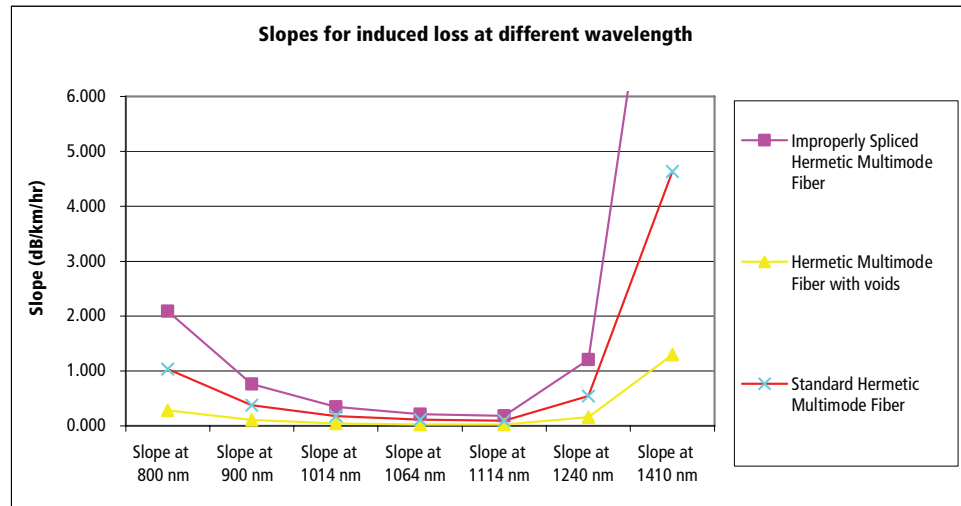
A standard Ge-doped 50 μm core carbon-polyimide-coated fiber was manufactured with voids in the cladding as described in the previous section. A cross-sectional view of the fiber is shown in Figure 5b. The fraction of voids in the cross-sectional area of this fiber is approximately ~10-12%. The diameter of the fiber is ~140 μm (i.e. ~12% larger than a standard 125 μm fiber).

One kilometer of fiber with voids was placed in the hydrogen test chamber along with a 1-km length of standard 50/125. Both fibers were coated with carbon and polyimide. Special care was taken to ensure that the splice between the void containing fiber and the feed-through fiber was protected to prevent “short-circuit” H_2 diffusion to the GTLs (Figure 7). The H_2 chamber was then heated to a temperature of 200°C and loaded with hydrogen to a pressure of 1500 psi. The optical attenuation spectrum was monitored on-line as a function of time for both these fibers, and the growth rate of attenuation in the 1064 nm region is reported in Table 1. We have also included in this table the test results of a fiber with voids where the splice with the feed-through fiber was not properly protected. It is clear that there is significant leakage of hydrogen through this interface point. Figure 9 displays the rate of attenuation increase (in dB/km/hr) for this group of fibers under the H_2 ingress conditions described previously. The attenuation measurement was performed in the 800 nm to 1410 nm spectral range.

Table 1: Spectral Attenuation Increase in db/km/hr for three different fibers at 200°C, 1500 psi of H_2 , and improved performance of GTL fibers over standard hermetic fibers

(DB/KM/HOUR)	SLOPE AT						
	800 NM	900 NM	1014 NM	1064 NM	1114 NM	1240 NM	1410 NM
Improperly Spliced Multimode GTL Fiber	2.092	0.763	0.344	0.213	0.181	1.206	11.620
Hermetic Multimode GTL Fibers (with voids)	0.282	0.109	0.044	0.027	0.023	0.158	1.299
Standard Hermetic Multimode Fiber	1.037	0.373	0.176	0.111	0.094	0.542	4.632
Improvement Factor for GTL Fibers, over Standard Hermetic Fibers	X 3.3	X 3.1	X 3.6	X 3.7	X 3.7	X 3.1	X 3.2

Figure 9: Spectral Attenuation Increase as a function of Wavelength for different Fibers



The data presented in Figure 9 shows that in the vicinity of the 1064 nm wavelength, the rate of attenuation increase of the fiber containing voids (illustrated by the triangle) is lower than that of the standard fiber (illustrated by the x) by approximately a factor of 4.

Finally, if we take into account that the diameter of the GTL fibers is 12% greater than that of the standard fiber and the concentration of hydrogen in the GTL fiber is therefore decreased by this factor (as described in the section on the permeation time constant), the GTL fiber exhibits improved performance by a factor of $(4/1.12) \sim 3.7$. The last row in Table 1 describes the level of improvement provided by the GTL fibers as a function of wavelength, relative to standard fibers. Geometric factors such as larger fiber diameter have been taken into account in this analysis.

It is clear from Table 1 that the level of improvement provided by the GTL fiber is strongly dependent on wavelength. This is not surprising since the growth rate of the attenuation is not expected to depend linearly on the concentration of hydrogen across the entire spectrum. However, in the 1064 nm region, a region of much interest to DTS users, the growth rate of the background attenuation level due to hydrogen ingress appears to be linearly dependent on the concentration of hydrogen present in the fiber, particularly at the temperatures and hydrogen partial pressures of our experiment.

Fiber Lifetime Predictions

Predicting fiber lifetimes, in a real downhole deployment, where hydrogen ingress is the dominant failure mechanism is a notoriously difficult problem. This is primarily because one of the key parameters, the actual hydrogen partial pressure, required to make a reasonable prediction is unknown and varies significantly from well to well. However, it is still possible to predict the attenuation increase in a specific region of the spectrum on the basis of assumed H_2 partial pressures.

If we assume that the H_2 partial pressure in a well is a fraction of an atmosphere, e.g. ~ 1 psi, then assuming that the attenuation growth rate depends linearly on hydrogen partial pressure, we obtain that the growth rate at 1064 nm is $\sim 0.027/1500$ dB/km/hr/psi. Over a period of one year the background attenuation increases by ~ 0.16 dB/km. If the dynamic range of the system is such that it can tolerate an attenuation increase of ~ 1 dB/km, we obtain a lifetime of ~ 5 -7 years at 200°C . It is important to note that the majority of oil wells deployments are at temperatures $\sim 150^\circ\text{C}$, and at these temperatures, given that the permeation constant is $\sim 10\times$ longer than it is at 200°C , one can expect significantly longer lifetimes. Note that the growth rates used in the current example for a typical multimode fiber

are typical of what is used in the industry. AFL has recently started to manufacture their second generation of hermetic optical fibers (using improved glass chemistry and carbon) whose hermetic performance is ~ 3-4 times better than the generation of fibers used in the present study¹². Hence one can speculate that the new generation of fibers (different core chemistry etc.) when combined with the present design of GTL fibers, should provide significantly enhanced lifetimes ~10-15 years, at moderately low temperatures and H₂ partial pressures.

Conclusions

In this work we have defined parameters to characterize the performance of hermetic coatings on optical fibers. We have also presented arguments indicating why a larger form factor fiber may be more advantageous in minimizing the effects of hydrogen ingress. We have introduced novel optical fiber designs (GTL fibers) that are theoretically predicted to reduce the effects of hydrogen ingress by factors of as much as 10 or greater, depending on the fraction of voids present in the fiber cross-section. These predictions have been verified experimentally, for both single-mode and multimode carbon coated fibers. We find that the improvement in hydrogen resistance is also dependent on wavelength, not unexpectedly, since the reaction of hydrogen with defects in the glass does not necessarily scale linearly with the concentration of H₂ molecules in the glass at all temperatures and pressures. Finally, the present design of GTL fibers in combination with novel core glass chemistries is expected to achieve fiber lifetimes in the 10-15 year range in typical downhole deployments.

References

1. R. Normann et al: Proc. 26th Workshop on Geothermal Reservoir Engineering, 2001.
2. James J. Smolen and Alex van der Spek: Distributed Temperature Sensing, A Primer for Oil and Gas Production, 2003.
3. J. Wysocki: Reduction of Static Fatigue of Silica Fibers by Hermetic Jacketing, Applied Physics Letters, 34 (1), January 1979.
4. S. Divita, U.S. Patent No. 4,028,080.
5. E. Hanson U.S. Patent No. 4,512,629.
6. C. Kao, U.S. Patent No. 4,183,621.
7. R. G. Huff, F. V. Di Marcello and A. C. Hart, "Amorphous Carbon Hermetically Coated Optical Fibers," Technical Digest for Optical Fiber Communication Conference, Paper TUG-2 1988.
8. P. J. LeMaire, K. S. Kranz, K. L. Walker, R.G. Huff and F. V. DiMarcello, "Hydrogen permeation in optical fibers with hermetic carbon coatings," Electron Lett., vol. 24, pp. 1323-1324, 1988.
9. F. V. DiMarcello, R.G. Huff, P. J. LeMaire and K. L. Walker, U.S. Patent No. 5,000,541.
10. H. Aikawa, Y. Ishiguro, A. Inoue, M. Hamada, K. Osaka and M. Watanabe, Sumitomo Electric Technical Review, No 34, June 1992.
11. D. Doremus, Glass Science, John Wiley.
12. AFL Internal Memo, 2005.



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