Reliability of low-index polymer coated double-clad fibers used in fiber lasers and amplifiers

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Abstract. The reliability of low-index polymer coated double-clad (DC) fibers used in the manufacture of fiber lasers and amplifiers has not received adequate attention. This paper evaluates the mechanical reliability of fibers, using standard fiber optic test procedures, and compares the performance of the DC fibers to the GR-20-CORE standard adopted by the industry. An 85 °C hot water soak test is proposed as an accelerated test to evaluate a low-index polymer coated DC fiber performance with prolonged exposure to temperature and humidity conditions experienced during storage and operation of fiber lasers. The test is used to evaluate DC fibers with three different coatings, including a specially engineered coating, and benchmark fibers from competitors. The data in this paper demonstrate that a dual acrylate coated DC fiber, using the specially engineered coating, has median failure stress values of over 700 kpsi and an average stress corrosion parameter of 21, well exceeding the recommended industry minimum values of 550 kpsi and 18, respectively. The accelerated temperature and humidity aging test clearly demonstrates that DC fibers with specially engineered coatings have 2 to 3 orders of magnitude better optical reliability. Such remarkable optical and mechanical performance significantly alleviates long term reliability concerns of fiber lasers and amplifiers. [DOI: 10.1117/1.3615653]

Subject terms: fiber lasers and amplifiers; double-clad fibers; mechanical and optical reliability; fiber characterization.

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1 Introduction

Fiber lasers for industrial, military, scientific, and medical applications are now ubiquitous. Active and passive fibers are used in fiber lasers as gain media, for numerous fiber-based components, and for beam delivery. To date, much of the discussion on the reliability of fibers for fiber lasers has been focused on photodarkening of the rare earth doped fibers.[1,2] Low-index polymer coatings play an important role in guiding the pump light used to power the gain media. Low index polymer coatings are based on fluoroacrylates and silicones. Fluoroacrylate coatings have been used in different formulations with varying physical properties including refractive indices to achieve different numerical apertures (NAs). Hard polymer clad silica fibers use fluoroacrylate-based low index polymer coatings.[3] Similar fluoroacrylate-based coatings are used for double-clad (DC) fibers. Spectral characteristics and mechanical reliability of hard polymer clad silica fibers has been reported.[4–6] However, the optical reliability of low index polymers and their impact on the reliability of fiber lasers is not readily available.

A typical DC fiber includes a core, which carries the signal light, a first cladding surrounding the core, which carries the pump light, and a second cladding, which helps contain the pump light in the first cladding. Although the second cladding can be a fluorosilicate glass, the index of such glass can barely provide NAs of 0.30, significantly below NAs of $\geq$0.46 typically needed for DC fibers. Low-index polymers with refractive indices of $\leq$1.38 provide desired NAs $\geq$0.46.

Passive DC fibers are used to transport pump and signal light to and from the active fiber and are used in components such as gratings, pump combiners, taps, filters, isolators, and acousto-optic modulators. In an active fiber, the pump light is transported in a noncircular first cladding until it is absorbed by the lanthanide dopants in the core. The role of the low-index polymer is to reliably contain the pump light in the first cladding over the life of the laser. Low-index polymer-coated fibers should not only be robust to mechanical handling, but also reliably perform their function over the temperature and humidity conditions experienced during storage and operation.

Because fiber manufacturers have not universally provided well-engineered polymer coatings for mechanical and optical reliability, laser manufacturers have either lived with fibers of unknown reliability or resorted to such methods as potting the DC fibers to create a barrier to moisture ingression and mechanical damage. However, since moisture diffusion is relatively rapid in polymers, potting the fibers in polymers is expected to only marginally improve reliability. A more lasting solution is to engineer the low-index polymer to withstand the deleterious effects of high temperature and humidity encountered during storage and operation.

Unlike fibers for telecommunications, where the coating performs the sole function of providing mechanical protection, polymer coatings used for DC fibers perform both mechanical and optical functions. It is therefore imperative to understand both the mechanical and optical reliability of

DC fibers using low-index polymer coatings. This paper addresses the mechanical and optical reliability of DC fibers and the significant reliability enhancements achieved with specially engineered low-index polymer coatings.

2 Damage Mechanisms Related to Low-Index Polymer Coated Fibers

Improper handling of polymer coated fibers can cause local delamination of the coating from the inner cladding that can scatter pump light. The scattered pump light may be partially absorbed by the coating and cause local hot spots and potentially catastrophic failure of the fiber.

Polymer coatings, including low-index fluoroacrylate coatings, degrade upon exposure to elevated temperature and humidity. It is well established that improved performance at high temperature and humidity is a good indicator of long term performance in real-life temperature and humidity. DC fibers used in fiber lasers operate both at elevated temperatures and in humid environments, and industrial systems require long term operation at such conditions. The coating related cladding attenuation of the fiber can increase with exposure to humidity at elevated temperatures. Such increase in attenuation can cause loss in system efficiency, as well as have an impact on long term reliability of a fiber laser.

As low-index polymer coated fibers are being widely used in fiber lasers and amplifiers, the mechanical performance and reliability of these fibers is of significant interest to fiber laser manufacturers. Mechanical reliability standards have been set for optical fibers used in the telecommunication industry. GR-20-CORE, Generic Requirements for Optical Fiber and Optical Fiber Cable,[7] is a universal standard adopted by the fiber industry and can be adopted for mechanical reliability of DC fibers. Since GR-20-CORE is geared toward 125-μm diameter fibers, this paper presents and compares performance of 125 μm DC fibers to this standard. GR-20-CORE, however, does not cover reliability with respect to optical performance of DC fibers. This paper outlines a test to benchmark reliability of DC fibers using low-index polymers.

3 Experimental Set-Ups

All DC fibers used in this study are drawn to 125 μm cladding diameters, with a fluoroacrylate based low-index polymer coating. Three different fluoroacrylate based low-index polymer coatings, Coating A, B, and C, were evaluated. Of these, we specially engineered Coating C for improved resistance to elevated temperature and humidity. The refractive indices of the three coatings were nominally the same (1.37) and were indistinguishable from normal batch to batch variations of a single type. The various physical properties of the coating were kept the same to ensure that draw conditions and cure levels of the fibers were not varying.

Since fluoroacrylate coatings tend to have low modulus values (5 to 30 MPa) and are not tough enough, a protective high modulus (500 MPa) telecom grade secondary acrylate coating is applied on top of the fluoroacrylate coating. The robust secondary coating mechanically protects the low-index coating from nicks and scratches that can cause light to leak from the fiber, resulting in localized hot spots or catastrophic failures. In each case, the fluoroacrylate coating was kept to a nominal thickness of 25 μm. The same telecom grade secondary coating was applied to a nominally same thickness of 37 μm on top of the fluoroacrylate coating.

Three lots of round fibers were drawn with three different batches of low-index fluoroacrylate coating. Optical grade pure silica glass rods were used to draw the round fibers. Pure silica glass was chosen to determine the cladding background loss associated with low-index coating and to monitor changes in loss upon exposure to high temperature and humidity. Since non-PM active DC fibers are noncircular, an octagonal shaped 125 μm Yb-doped fiber was also drawn to compare mechanical performance with round fibers and study the effect of the preform machining step often used in the fabrication of octagonal shaped active fibers. Octagonal, as well as round fibers, were tested to 100 kpsi proof test level prior to performing mechanical and optical performance tests described below to evaluate their relative performance.

Mechanical performance of low-index polymer coated fibers was evaluated per accepted fiber optic test procedures.[8,9] An MTS Synergie 200 tensile pull tester was used to determine tensile strength values and generate Weibull probability plots and the stress corrosion parameters for different lots of fibers. Thirty half-meter gauge length samples were used from each lot of fiber to measure the tensile strengths, at stress rates of 4%/min, and generate the Weibull plot. The median failure stress, 15% failure stress values and Weibull slope (m-value) were determined for each lot and compared to the GR-20-CORE requirements. The stress corrosion parameter (n_d) was determined by testing 14 samples from each lot at each of 4 different stress rates spanning a range from 0.064 to 26%/min.

Spectral attenuation of the DC fibers was measured using a fiber optic industry standard PK2500 spectral attenuation measurement unit. The launch NA and spot size used for the study were 0.32 and 300 μm, respectively. The loss at $\sim$1100 nm was used as a measure of the background cladding attenuation. Attenuation at this wavelength was also used to monitor the effects of temperature and humidity on the optical performance of the coating. Two different tests were used to determine the effects of elevated temperature and humidity on optical performance. The first included exposure of the DC fibers to 85 $\pm$ 2 °C and 85 $\pm$ 5% relative humidity (RH), as recommended by GR-20-CORE,[7] using a Themotron environmental chamber. Cladding attenuation at $\sim$1100 nm was monitored after periodic intervals of time to evaluate the impact of elevated temperature and humidity. While GR-20-CORE recommends a 720 h exposure, substantially longer exposure times were used for this study. A second test was devised to accelerate the coating related attenuation and benchmark performance of different coatings. The test involved immersing a known length of fiber in a hot water bath maintained at 85 °C. The cladding attenuation at $\sim$1100 nm was measured using a cutback technique,[10] and was monitored at regular intervals to observe the changes in attenuation.

4 Results and Discussion

To understand the mechanical reliability of low-index polymer coated fibers, a variety of tests including failure stress, stress corrosion parameter, and coating strip force studies, were conducted both on round and octagon shaped DC fibers

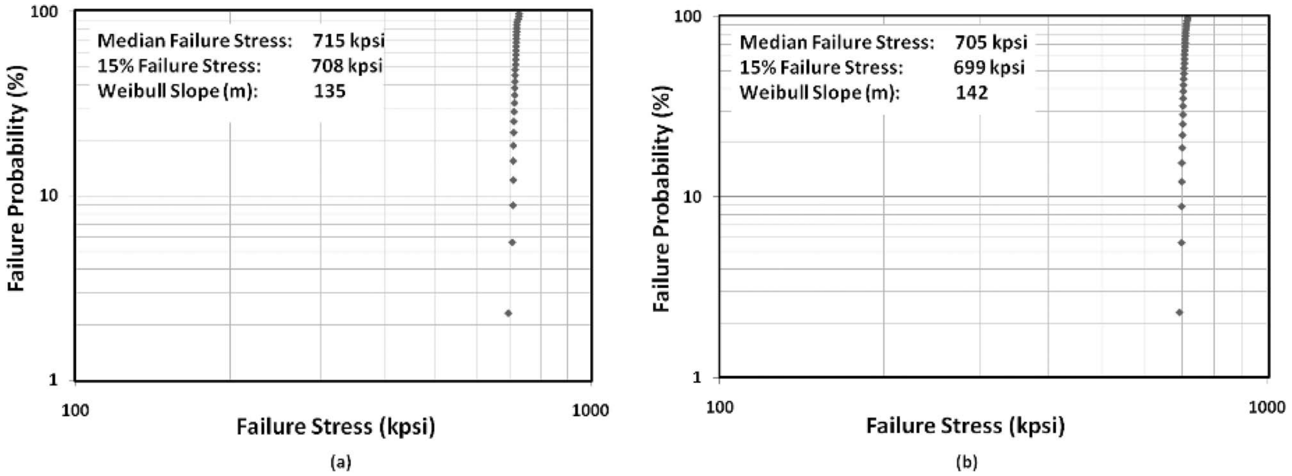

Fig. 1 Weibull probability plots for (a) round and (b) an octagonal shaped DC fiber drawn with a specially engineered low-index polymer coating (Coating C).

using Coating C. In addition, elevated temperature and humidity tests were conducted to understand the optical reliability of the fibers with different fluoroacrylate coatings.

4.1 *Mechanical Reliability*

Weibull probability plots for round and octagonal shaped DC fibers are presented in Fig. 1. Both round and octagonal fibers have tensile strength values approaching 770 kpsi for pure silica.[11] Table 1 presents a summary of various mechanical properties evaluated in this study. The strength values have been calculated based on the actual cross sectional areas for round and octagonal shaped fibers. The median failure stress value for an octagonal shaped fiber (705 kpsi) is slightly lower compared with that for round fibers (712 kpsi), but is remarkably high considering that the preform underwent a machining operation, and is well above the GR-20-CORE recommended minimum of 550 kpsi.

It is also noteworthy that not a single low strength failure is observed in Fig. 1, either for round (90 samples tested) or octagonal shaped (30 samples) fibers. The probability of finding weak sections in the fiber that can fail at low stresses is quantified by the *m*-value. The *m*-value is the slope of the line joining the median failure stress and 15% failure stress values. An *m*-value in the range of 50 to 100 is considered respectable in the industry. The high average *m*-values for round (140) and octagonal (142) shaped fibers are remarkable, and indicate that the high tensile strengths are consistent along the length of the drawn fibers, giving confidence to the user that the fibers can withstand bending stresses experienced in the coiled configurations.

The stress corrosion parameter (n_d) is a useful parameter to determine the mechanical reliability of fibers.[12] Since the n_d value appears as an exponent in fiber lifetime models,[12] seemingly small changes in n_d values can result is substantial changes in lifetimes. The n_d value is derived from the slope of the log-log plot of failure stress and the corresponding stress rate per FOTP-28.[8] GR-20-CORE requires that optical fibers have an n_d of $\geq$18. Figure 2 presents a typical plot generated to determine the value of n_d for an octagonal shaped fiber.

Table 1 Comparison of mechanical properties of round and octagonal shaped DC fibers drawn with a specially engineered low-index polymer coating.

	Weibull probability level						
	50%		15%				
Fiber lot	Kpsi	Gpa	Kpsi	Gpa	Weibull slope (m)	Stress corrosion parameter (n_d)	Strip force (lbf)
GR-20 Requirement	≥550	≥3.80	≥455	≥3.14	–	≥18.0	0.2 to 2.0
Round Lot A	717	4.94	709	4.89	120	22.8	0.99
Round Lot B	715	4.93	708	4.88	135	19.8	0.96
Round Lot C	709	4.89	702	4.84	164	21.5	0.89
Average	712	4.92	706	4.87	140	21.3	0.95
Std. Deviation	4.2	0.03	3.8	0.03	22	1.5	0.05
Octagon Lot D	703	4.85	697	4.81	142	22.2	0.92

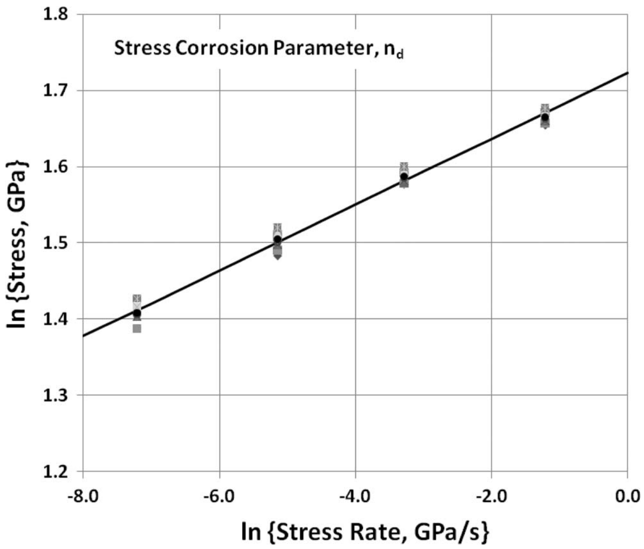

Fig. 2 A typical plot of ln(stress) versus ln(stress rate) for an octagonal shaped fiber that is used to determine the stress corrosion parameter (n_d).

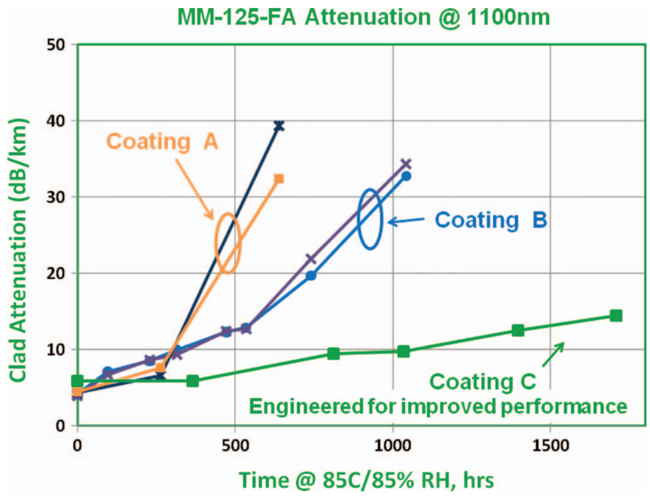

Fig. 3 Cladding attenuation changes for three DC fibers, drawn with low-index polymer coatings A, B, and C, when exposed to 85 °C and 85% relative humidity.

Data in Table 1 indicate that average n_d values for both round (>21) and octagonal (>22) shaped DC fibers well-exceed the ≥18 requirement of GR-20-CORE. These higher values indicate that, under similar real life conditions of deployment, the lifetime of these double clad fibers will be orders of magnitude higher than the lifetime predicted for a minimum n_d value of 18. It is again notable that a surface grinding operation performed to realize an octagonal shape has no impact on the n_d value and performance similar to round fibers can be achieved by following appropriate machining and cleaning procedures.

The force required to strip the coating, called the strip force, is a useful practical parameter, as these DC fibers are constantly mechanically stripped to splice fibers together while building fiber lasers. GR-20-CORE recommends that the strip force is optimally within the range of 0.2 to 2.0 lbf for ease of use. The strip force of dual-acrylate coated DC fibers was measured per FOTP-178.[9] The DC fibers with low-index polymer coating as the primary coating and a robust telecom grade secondary have strip force values around 1 lbf (see Table 1), making them easy to strip during the manufacture of fiber lasers.

4.2 *Optical Reliability*

Mechanical performance of optical fibers can degrade upon extended exposure to temperature and humidity. Accelerated aging tests involving exposure of the fibers to elevated temperatures and humidity have been devised to understand the propensity of fibers to degrade, as well as to bench mark different fiber-polymer coating systems, including hard clad silica fibers.[5,6] Mechanical performance of the DC fibers after such exposure has not yet been evaluated. However, it is anticipated that the onset of optical degradation will precede any mechanical degradation. As such, this study focused on the optical performance degradation of low-index polymer coated DC fibers.

Optical degradation of low-index polymers can lead to increased absorption or scattering of pump light, resulting in the degradation of laser output power. Low index polymer coated fibers exposed to moderate to high temperatures (40 to 85 °C) at 85% RH showed the same characteristic wavelength independent increase in spectral attenuation at different temperatures of exposure albeit at different rates. The similarity in response of the fibers at different temperatures indicates that the mechanism of moisture related degradation is not altered, and elevated temperatures can be used to accelerate the test and obtain data in practical time periods without altering the underlying mechanism. Hence, relative performance of the coatings under accelerated conditions may be a reasonable indicator of relative performance in real life.

Figure 3 shows cladding attenuation changes for three DC fibers, drawn with low-index polymer coatings A, B, and C, exposed to 85 °C and 85% RH. Coatings A and B show a rapid increase in attenuation, while Coating C, the fiber with specially engineered coating, shows only a modest increase, even after 1500 h of exposure. NAs of the exposed samples were measured at different lengths ranging from 2 to 10 m. The measurements indicate a length dependence of NA with the shortest length approaching the launch NA. If the refractive index of the low index polymer were to change upon exposure, no length dependence of NA would have been observed. It is therefore concluded that the observed attenuation change is a result of true coating related losses, rather than changes in refractive index.

The 85 °C/85% RH study does not explicitly reveal the optical degradation of the low-index polymer. More specifically, because OH ingression into glass also increases background attenuation,[13] it is important to distinguish the coating-related from glass-related attenuation changes. Figure 4 shows the spectral attenuation changes for a glass fiber coated with a low-index polymer. The spectral curve prior to exposure (0 h) provides the baseline spectral features for comparison. Upon exposure, both wavelength-dependent and -independent attenuation changes are observed. The 940- and 1240-nm attenuation peaks are attributable to –OH overtones in silica glass,[13] and the attenuation increase below 800 nm is believed to originate from glass defects resulting from moisture ingression. A significant wavelength-independent component of attenuation is also observed and attributed to light scattered by the low-index polymer upon exposure to

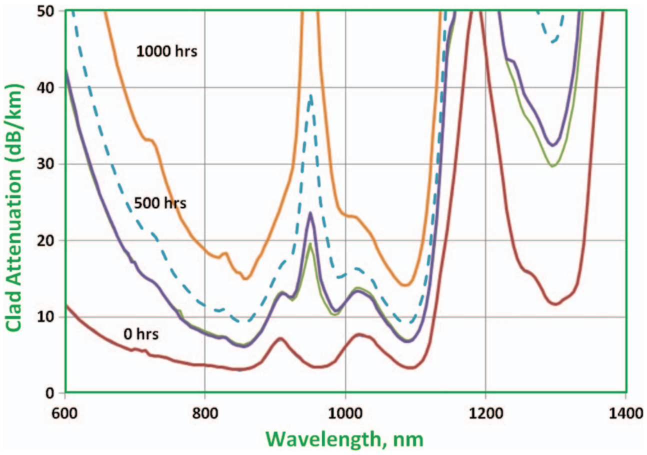

Fig. 4 Spectral attenuation changes for a DC fiber coated with low-index polymer coating, Coating B, upon exposure to 85 °C and 85% relative humidity.

moisture. The 85 °C/85% RH test provides enough time for moisture to not only degrade the low-index polymer, but also to penetrate the glass, making it difficult to independently evaluate the coating performance and benchmark different coatings.

The diffusion of moisture into a polymer is significantly faster than into glass, so a shorter duration test at a significantly elevated surface concentration would be better to evaluate the coating performance. And, monitoring the attenuation at a wavelength such as ∼1100 nm, which is minimally affected by the attenuation peaks related to –OH in glass (and ytterbium related absorption peaks in the case of ytterbium doped DC fibers), is better suited for monitoring coating performance. Spectral attenuation changes observed on fibers exposed to 85 °C hot water were similar to those exposed to 85% RH, indicating once again that the mechanism of moisture related coating degradation was not altered. Hot water immersion tests can therefore be reasonably used to benchmark coating performance in real life conditions.

Attenuation changes at ∼1100 nm, in 85 °C hot water bath, for fibers drawn with three different coatings are shown in Fig. 5. Figure 5(a) shows that fibers with Coating A and B degrade in a matter of 1 to 3 h, with attenuations increasing to 50 to 300 dB/km. In contrast, fibers drawn with the specially engineered low-index polymer, Coating C, perform exceedingly well with negligible increase in attenuation, in comparable time frames. Figure 5(b) shows that multiple batches of DC fibers drawn with Coating C show remarkable resilience for hundreds of hours in 85 °C hot water. Increases in cladding attenuation, which are observed beyond 500 h of exposure, are believed to be due to eventual moisture ingression into the glass. Since DC fibers drawn with Coating A and B degrade in 1 to 3 h while DC fibers drawn with Coating C shows a negligible increase in attenuation up to 500 h, it can be concluded that the specially engineered coating provides a 2 to 3 orders of magnitude better resistance to temperature and humidity under accelerated conditions. Furthermore, since testing at accelerated conditions does not appear to change the degradation mechanism, DC fibers with this specially engineered coating can be expected to have similar improvement in lifetime at typical conditions encountered during storage and operation of fiber lasers.

With increasing deployment of fiber lasers, a multitude of component and laser manufacturers are becoming increasingly conscious of the reliability of their devices, and some are taking steps to do incoming inspection of fibers. Avensys-ITF Labs, a supplier of high-power combiners, has adopted the recommended hot water soak test to qualify fibers. They performed a 10-h water soak test to qualify fibers from three fiber suppliers and contributed Fig. 6 for this article to report the usefulness of the test to distinguish performance of commercially available DC fibers. Nufern fiber showed no increase in loss, while the fibers from two other vendors rapidly degraded. Based on this data, they attest that DC fibers drawn with the specially engineered coating from Nufern, are far superior to any other fibers they have tested to date.

Avensys-ITF Labs evaluated far field intensity profiles of fibers with specially engineered Coating C, from Nufern, along with DC fibers from two other vendors. All fibers

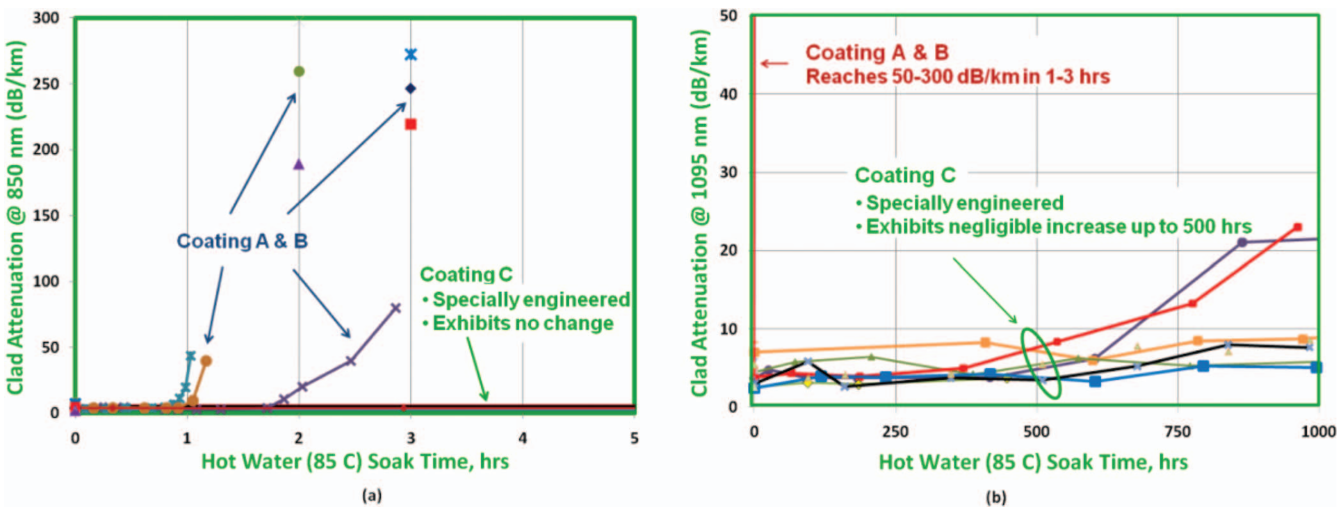

Fig. 5 Increase in cladding attenuation of DC fibers drawn with Coating B and a specially engineered low-index polymer Coating C, upon soaking in 85 °C hot water for (a) short duration and (b) for long duration of time.

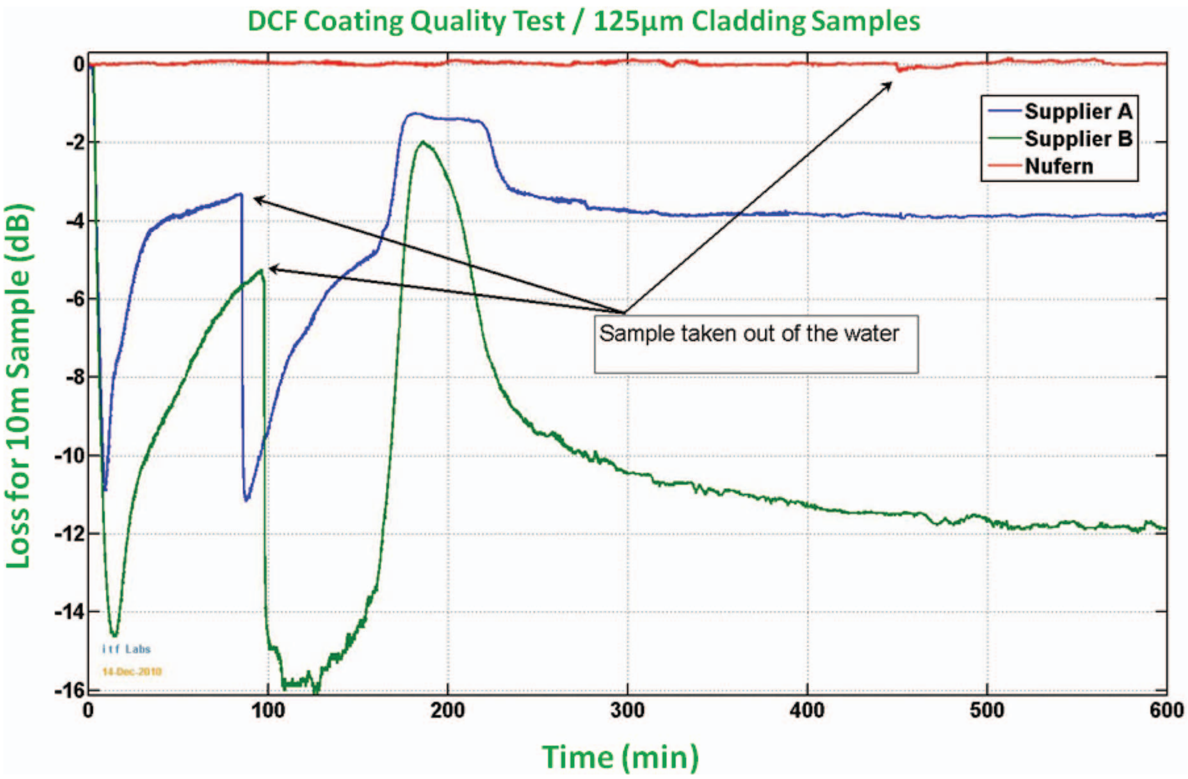

Fig. 6 Performance of three commercially available DC fibers subjected to the hot water soak test. (Courtesy of Avensys-ITF Labs.)

supported the far field profile of the source before exposure to hot water. Far field intensity profiles for the exposed fibers (10 h in 85 °C hot water) were compared to the reference profile (Fig. 7). Nufern fiber did not show any degradation in the far field intensity profile, consistent with no decrease in transmission (Fig. 6). However, the far field intensity profiles of the two other fibers degraded as anticipated from the transmission losses seen in Fig. 6. The post exposure profiles (Fig. 7) show a severe reduction in the intensity of the modes emanating at wider angles (higher order modes).

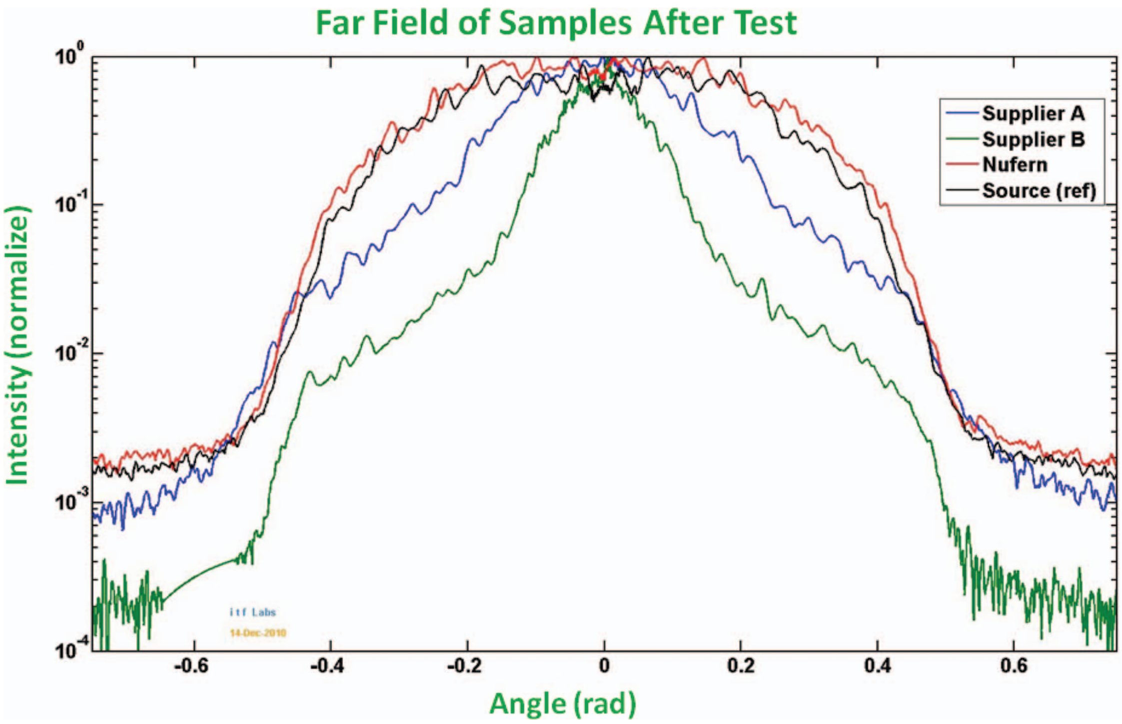

Fig. 7 Comparison of far-field intensity profiles of three commercially available fibers after exposure to hot water. (Courtesy of Avensys-ITF Labs.)

Such a preferential attenuation of the higher order modes, which carry a significant amount of power, in an unqualified low index polymer coated fiber is of significant consequence to both component and laser manufacturers. For combiner and grating manufacturers, the increased losses can mean failure to meet coupling efficiency or insertion loss specifications. For a laser manufacturer, employing typically tens of meters of passive and active DC fibers, an increase in the loss can mean an unacceptable degradation in system efficiency.

5 Conclusions

To date, the reliability of low-index fluoroacrylate coatings has not received adequate attention. To our knowledge, this paper is the first detailed study on mechanical and optical reliability of low-index polymer coated DC fibers. This study shows that dual acrylate coated DC fibers, with a specially engineered low-index polymer as the primary coating on the inner cladding and a robust telecom grade secondary coating to protect the low-index primary, can provide excellent mechanical and optical reliability.

Both round and octagonal shaped DC fibers exhibit median tensile strength values (>700 kpsi) and average stress corrosion factors (>21), well exceeding the optical fiber standards. A new standard for evaluating temperature and humidity related optical reliability of low-index polymer coated DC fibers is proposed. It is shown that the specially engineered low-index polymers can withstand accelerated aging, in 85 °C hot water, for hundreds of hours. The specially engineered coating has 2 to 3 orders of magnitude longer lifetime under accelerated conditions and significant lifetime enhancements can be expected at real life conditions.

The availability of DC fibers with specially engineered low-index polymer coatings has significantly alleviated an important reliability concern for fiber lasers. However, we are yet unable to use accelerated tests to predict lifetimes in environmental conditions specified for operation and storage of fiber lasers. The task is further complicated by the fact that many laser manufacturers cannot determine the temperature of active fibers and components in their devices under the specified environmental conditions. Lifetime predictions under specific environmental conditions and laser designs remain a subject for future work.

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