Reliability of Double Clad Fiber Coatings for Fiber Lasers

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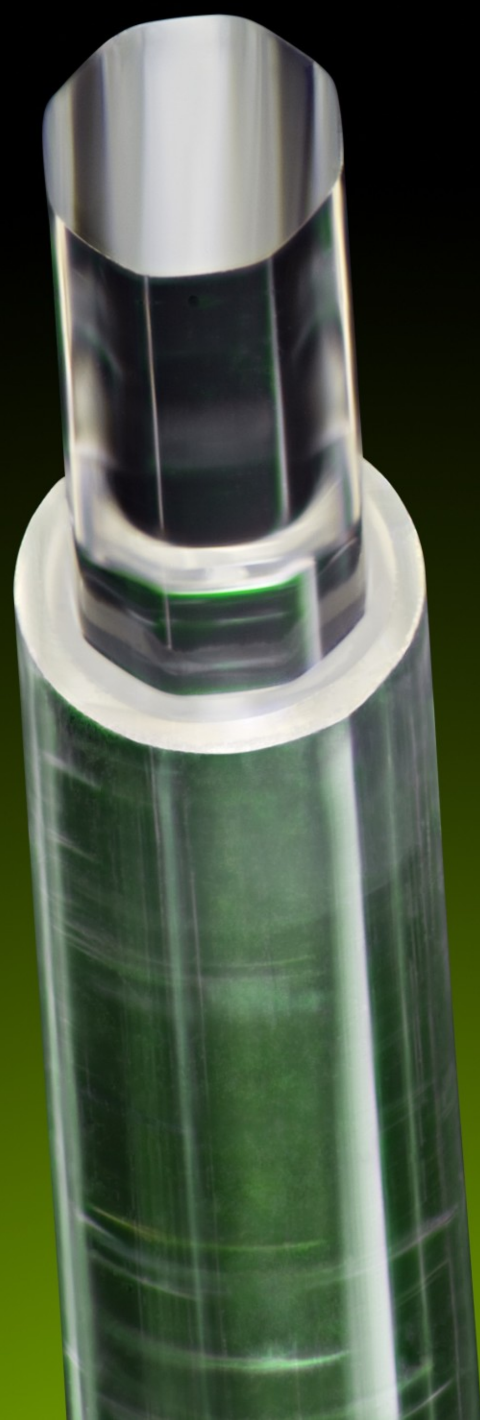

A synthetic confocal microscope image of an ytterbium-doped 20/400 double-clad laser fiber from Nufern. The octagon shape of the glass is shown, as are the dual polymer coatings carefully stripped back. Courtesy of Nufern.

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 reliability of fiber lasers has been focused on diode and fiber reliability. In the regime of fiber reliability, attention has primarily been given to photo-darkening of the double-clad fibers used as gain media. Low-index polymer coatings are key in guiding the pump light, and their mechanical and environmental reliability has not received due attention.

Because fiber manufacturers have not universally provided well-engineered polymer coatings for mechanical and optical reliability, laser manufacturers have either lived with fibers of questionable reliability or resorted to such methods as potting the double-clad fibers to create a barrier to moisture ingression and mechanical damage. And because 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.

A typical double-clad 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 numerical apertures (NAs) of 0.30, significantly below NAs of ≥0.46 typically needed for double-clad fibers. Low-index polymers with refractive indices of ≤1.37 provide desired NAs ≥0.46.

Passive double-clad fibers are used to transport pump and signal light to and from the gain medium (the active fiber) and are used in components including 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 not only should be robust to mechanical handling, but also should reliably perform their function over the temperature and humidity conditions experienced during storage and operation.

Unlike fibers for telecommunications, where the coating performs the sole function of providing mechanical protection, polymer coatings used for double-clad fibers perform both mechanical and optical functions. A dual acrylate coating system – in which the low-index polymer coating forming the first coating contacting the glass is followed by a rugged secondary coating to protect the relatively delicate low index coating – is essential for double-clad fibers. 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 burns. Dual-acrylate-coated double-clad fibers can exceed the stringent mechanical reliability standards set forth by Telcordia's GR-20 standard. Double-clad fibers with a dual acrylate coating can exhibit near-theoretical strength of silica. Measured typical median failure stress of 715 kpsi and a 15 percent failure stress of 708 kpsi significantly exceed the GR-20 standards of ≥550 kpsi and ≥455 kpsi, respectively. In addition, a stress corrosion parameter of 20 was measured, comfortably meeting the GR-20 requirement of ≥18.

The GR-20 standard provides guidelines for mechanical performance before and after exposure of fibers to 85 °C and 85 percent relative humidity for 720 hours (30 days) to ensure mechanical reliability. Although mechanical performance of polymer-coated glass fibers has been studied extensively in the telecommunications industry, little if any work has been carried out on the reliability in optical performance of low-index polymer-coated fibers for the fiber laser industry.

Degradation of low-index polymers with exposure to temperature and humidity can lead to losses by increased absorption or scattering of pump light, resulting in a degradation of laser output power. Figure 1 shows attenuation changes of three glass fibers, with various low-index polymer coatings, exposed to 85 °C/85 percent relative humidity. Coatings A and B seem to show a rapid increase in attenuation after a few hundred hours of exposure, while Coating C, the fiber with specially engineered coating, shows only a modest increase, even after 1500 hours of exposure.

It should be noted, however, that this 85 °C/85 percent study does not explicitly reveal the optical reliability of the low-index polymer-coated double-clad fibers. More specifically, because OH ingression into glass also increases background attenuation, it is important to distinguish the coating-related attenuation changes from increases in attenuation of the glass. Figure 2 shows the spectral attenuation changes for a glass fiber coated with a low-index polymer. The spectral curve prior to exposure (0 hours) to an 85 °C/85 percent relative humidity environment provides the baseline spectral features for comparison.

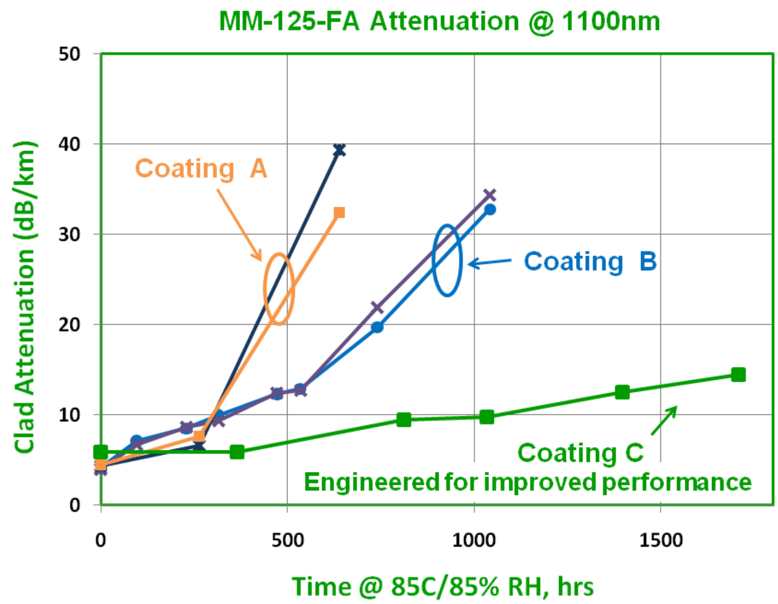

Figure 1: Cladding attenuation changes in a glass fiber coated with low index polymer. Courtesy of Nufern.

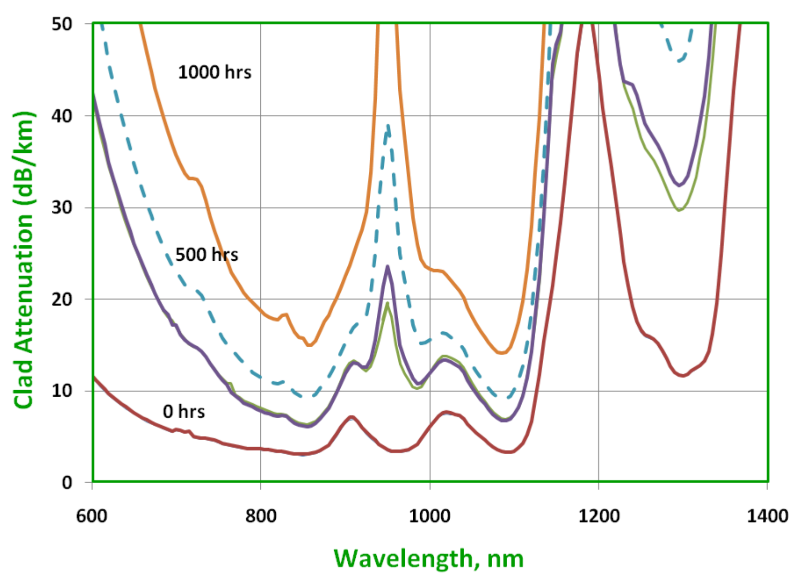

Figure 2: Spectral attenuation changes in a glass fiber coated with Coating B with exposure to 85°C/85 percent relative humidity. Courtesy of Nufern.

The baseline spectrum shows that the attenuation in the typical pump wavelength range before exposure to temperature and humidity is well below a negligible 0.01 dB/m. Upon exposure to temperature and humidity, both wavelength-dependent and -independent attenuation changes are observed. The 940- and 1240-nm attenuation peaks are attributable to –OH overtones in silica glass, and the attenuation increase below 800 nm is believed to be originating from glass defects resulting from moisture ingression. A significant wavelength-independent component of attenuation also is observed and is attributed to light scattered by the low-index polymer upon exposure to moisture. The 85 °C/85 percent relative humidity test provides enough time for moisture not only to degrade the low index polymer, but also to penetrate the glass cladding, making it difficult to independently evaluate the coating performance and to benchmark various low-index polymers.

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, is better suited for monitoring coating performance. The increase in attenuation at 1100 nm in an 85 °C hot water bath for fibers drawn with two different coatings is shown in Figure 3.

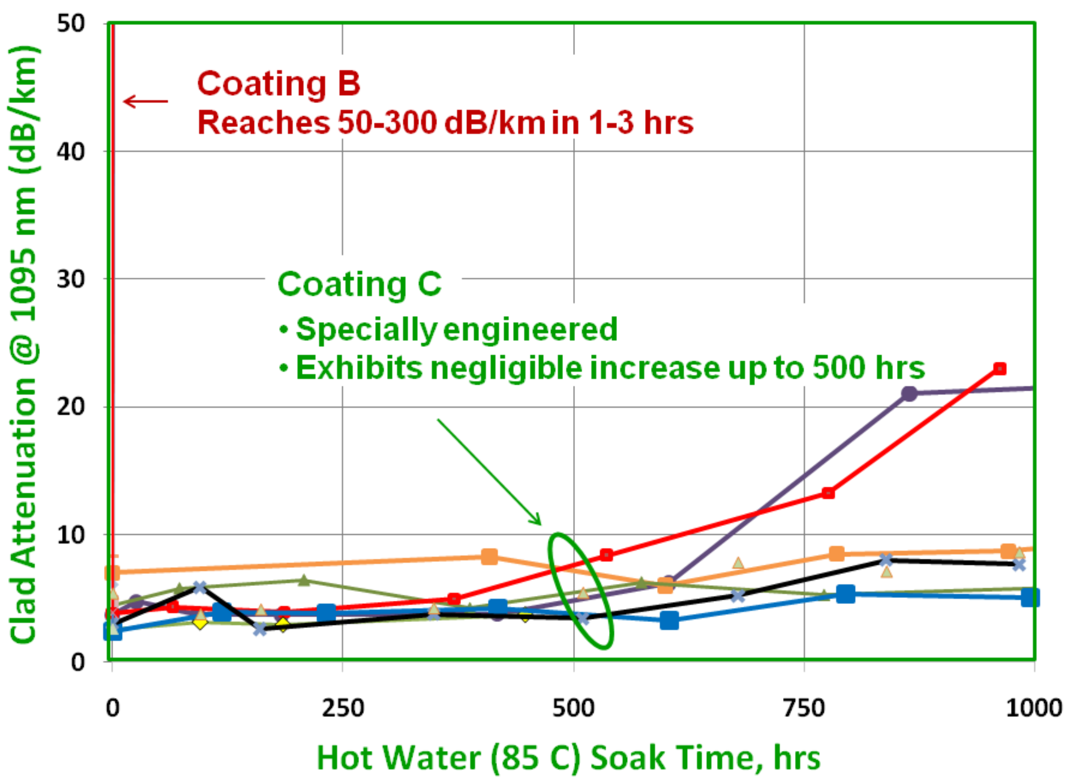

Figure 3: Increase in attenuation with time for fibers soaked in 85°C hot water. Courtesy of Nufern.

It is observed that fibers with Coating B degrade in a matter of one to three hours, with attenuations reaching 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, even after 500 hours of exposure. Clearly, a well-engineered low-index polymer coating, Coating C, can be two to three orders of magnitude better in performance, significantly alleviating reliability concerns.

Avensys-ITF Labs, a supplier of high-power combiners, has adopted the recommended hot water soak test to qualify fibers from various suppliers. It performed a 10-hour water soak test to qualify fibers from three fiber suppliers and contributed Figure 4 for this article to report the usefulness of the test and to encourage users of double-clad fibers to adopt this proposed standard to distinguish performance of commercially available double-clad fibers. The company also provided data (Figure 5) to demonstrate that the increased attenuation upon moisture ingression manifests itself as a severe restriction in the NA of the fiber. Components and lasers made with fibers that have poor reliability will experience output power degradation because of increased insertion losses and, in extreme cases, could fail catastrophically.

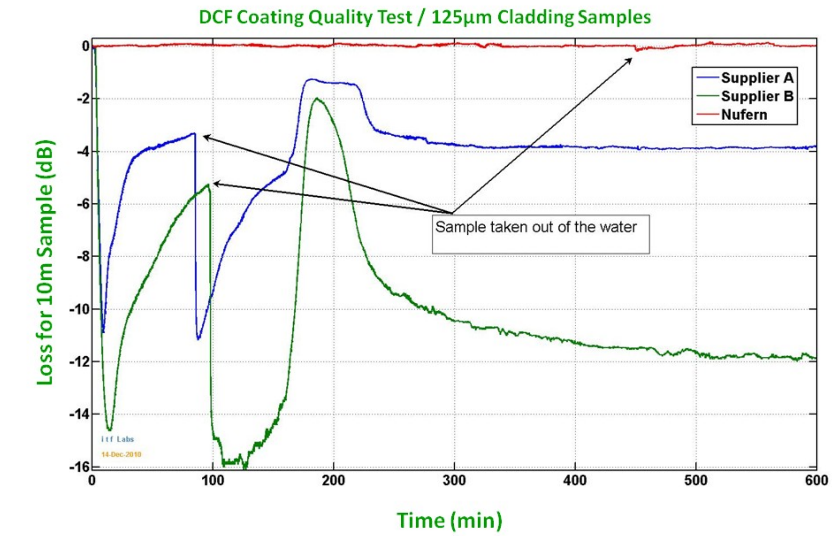

Figure 4: Performance of three commercially available double-clad fibers subjected to the hot water soak test. Courtesy of Avensys-ITF Labs.

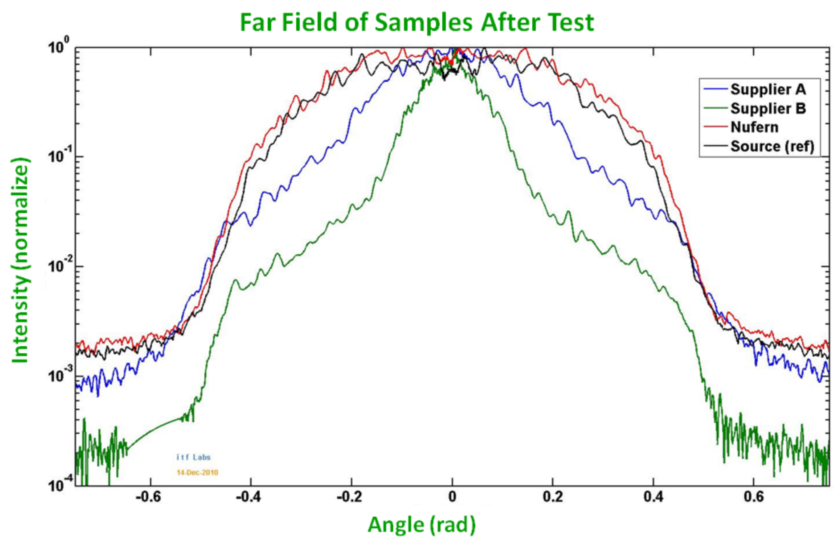

Figure 5: Numerical aperture of the commercially available fibers after exposure to hot water. Courtesy of Avensys-ITF Labs.

The availability of double-clad fibers with well-engineered low-index polymer coatings has significantly alleviated an important reliability concern for fiber lasers. Fibers with two to three orders of magnitude better optical reliability have been engineered and are commercially available. However, fiber manufacturers 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 made with passive fibers under specified environmental conditions. Lifetime predictions under specific environmental conditions and laser designs remain a subject for future work.

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