Reliability of optical fibers in a cryogenic environment

Eric A. Lindholm*, Andrei A. Stolov, Robert S. Dyer, Brian Slyman & David Burgess
OFS, Specialty Photonics Division
55 Darling Drive, Avon, CT 06001 USA

ABSTRACT

Optical fibers with various protective coatings were submerged in liquid nitrogen to 77°K then tested for mechanical and optical reliability. It was found that while all the fibers maintained strength after low-temperature exposure, the optical response varied depending on the protective coating. The optical attenuation observed for some fiber samples is due to axial shrinkage of the coating, which then leads to an elevated microbending loss. The behavior of the fiber coating at temperatures below the glass transition temperature is discussed.

Keywords: optical fiber, reliability, harsh environments, sensing

1. INTRODUCTION

As optical fiber sensors gain in popularity over electrically-based sensors, they are also finding utility in applications at the edge of environmental extremes. Optical fibers have been employed as data links and sensors in aerospace platforms where their light weight, high bandwidth, and immunity to electromagnetic interference are particularly valued.[1] Fibers have also been used for hydrogen leak detection while grating-based sensors monitor temperature and strain from the main engine to the liquid propellant fuel tanks.[2] In addition, applications for fibers in the cryogenic temperature range may be found in the industrial, medical, and geophysical markets.

Early work by Proctor, Whitney and Johnson found that silica fibers held at 77°K exhibited a higher tensile strength than fibers held in ambient conditions.[3] Subsequent work has established the concept of "inert" strength where the deleterious effect of moisture is removed when determining strength.[4] In the case of fiber measured in a cryogenic environment, the water is not removed (as in a vacuum) but rather immobilized; thus, without moisture to assist in crack growth, there is no time-dependent degradation in fiber strength, a.k.a. fatigue.

Perhaps a greater concern for fibers operating at cryogenic temperatures is the microbending loss induced by the fiber coatings due to the change in mechanical properties at low temperatures.[5] At room temperatures, most polymeric fiber coatings are soft and pliable. However, when a coating is cooled below its glass transition temperature (T_g), it will shift from a rubbery state to a rigid glassy state with a corresponding increase in the coating's Young's modulus.[6] At the same time, there is a reduction in the specific volume of the coating as dictated by the rubber to glass transition and the coefficient of thermal expansion (CTE). The difference between the glass CTE and the coating CTE results in an axial stress on the fiber leading to an increase in attenuation due to microbending. Lumholt et. al. demonstrated that different levels of microbending loss at discrete wavelengths on a singlemode fiber can be measured to create a simple low-temperature fiber sensor.[7] However, a fiber with a minimum induced loss would be preferable for most applications since microbending loss effects can interfere with data transmission or interrogation techniques such as distributed temperature sensing.

2. EXPERIMENTAL

For mechanical and optical reliability testing, 50μm core/125μm cladding multimode fiber was selected because it is the most common type of fiber used for distributed temperature sensing. In this study, the following fiber samples were prepared:

* Correspondence – Email: elindholm@ofsoptics.com

Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 73160Z

50µm core / 125µm cladding + 190µm primary / 245µm secondary UV-curable acrylate
≈ 400Å hermetic carbon / 190µm primary / 245µm secondary UV-curable acrylate
155µm thermal-cure polyimide
≈ 400Å hermetic carbon / 155µm thermal-cure polyimide
450µm thermal-cure silicone
≈ 400Å hermetic carbon / 450µm thermal-cure silicone

For the mechanical reliability test, 2m lengths of the fiber samples were made into loose coils and then submerged in liquid nitrogen at 77°K for a period of five minutes. The samples were bagged immediately after exposure and allowed to equilibrate overnight at room temperature. Both the control and exposed fiber samples were then tested for strength on an Accudex two-point bending tester at a strain rate of 4%/minute.

For the optical test, 100-meter fiber samples were prepared into loose coils about 6" in diameter and held together with wire ties. A 50µm launch fiber was wrapped around a mandrel and connected to the fiber under test with an ST adapter; the launch end was then attached to a Rifocs 850nm LED light source (model #257A). The opposite end of the test fiber was attached to a bare fiber adapter and a Rifocs 850nm power meter (model #555B).

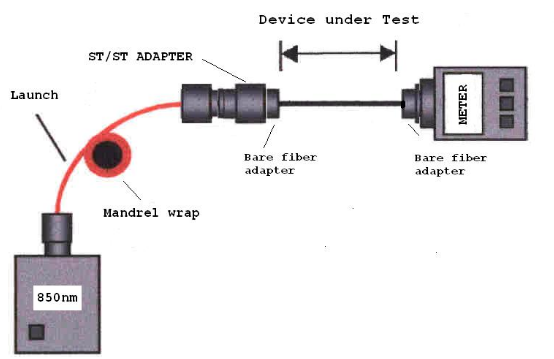

Fig. 1: Fiber power meter.

After connectorization, the test fiber was placed into a flat pan and the power meter zeroed. Liquid nitrogen was then carefully added to the pan so that the 100m loop was completely submerged (below):

Fig. 2: Optical fiber submerged in liquid nitrogen at 77°K.

After a minute, the optical attenuation at 850nm was recorded for the test fiber. The fiber loop was then removed from the pan and allowed to warm up under normal room temperatures; the recovery of the optical signal was also noted. For some of fibers tested, the attenuation was beyond the measurement capabilities of the power meter and 10m samples were prepared to repeat the test.

Thermal behavior of the coatings was characterized using a TA Instrument 2920 Differential scanning calorimeter at heating rate of 10°C/min in nitrogen environment.

3. RESULTS AND DISCUSSION

The results of the two-point bend strength testing may be seen below:

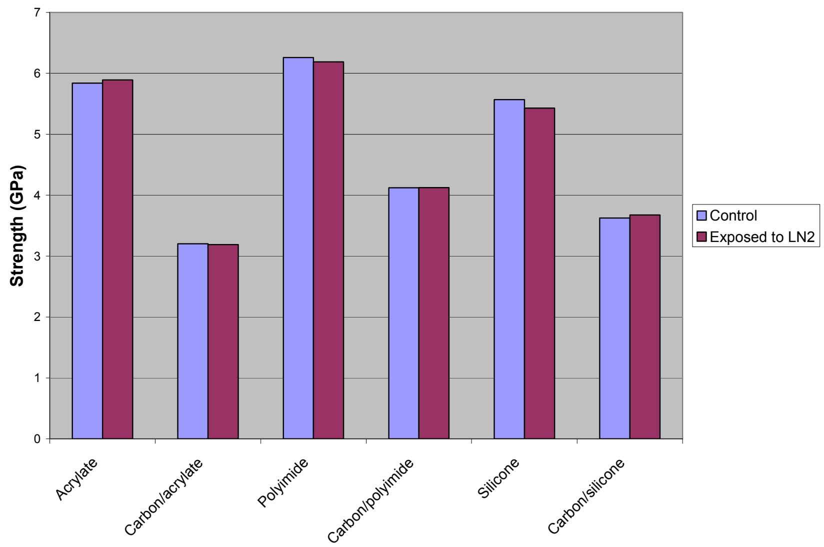

Fig. 3: Strength of fiber samples before and after exposure to liquid nitrogen.

At sufficiently low temperatures below the glass transition temperatures of the coatings, there is a concern that embrittlement of the coating will lead to flaws in the protective layer that degrade fiber strength. However, as the data indicate, no degradation in strength was noted after the five-minute soak test.

The optical transmission tests revealed wide differences in microbending loss for fibers exposed to cryogenic temperatures. Neither the polyimide or carbon/polyimide fiber samples exhibited an induced loss when exposed to liquid nitrogen; the carbon/acrylate fiber had an attenuation equal to 1.6 dB/km (standard acrylate was not tested.) However, the 100-meter loops of silicone and carbon/silicone fibers went dark after submerged in the liquid nitrogen. New samples of these fibers in 10-meter loops were subsequently prepared along with a carbon/silicone fiber jacketed with a 900µm layer of ethylene tetrafluoroethylene (ETFE) buffer.

	Equivalent loss (dB/km)
Polyimide	0
Carbon / Polyimide	0
Carbon / Acrylate	1.6
Silicone	221
Carbon / Silicone	212
Carbon / Silicone / ETFE	52.5

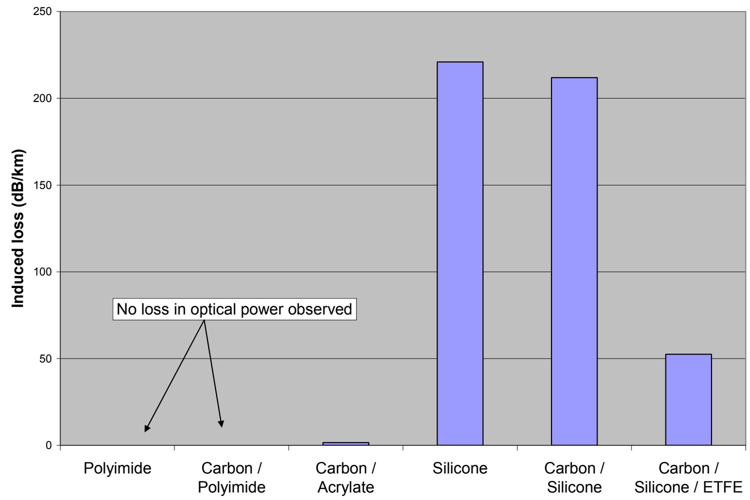

Fig. 4: Induced attenuation of fiber samples submerged in liquid nitrogen.

The data indicate that the silicone-coated fibers will go dark when exposed to cryogenic temperatures, with attenuations above 200 dB/km. The addition of the ETFE buffer to the carbon/silicone fiber appears to provide a "back relief" to the stresses imparted by the coating at the low temperature. For all fibers tested, the microbending loss was transient and the baseline transmission level was restored within a minute of removal from the liquid nitrogen bath.

Attenuation in optical fibers and factors responsible for it were considered in several theoretical studies.[8,9,10,11] To our best knowledge, there is still no theory which fully describes effects of optical fiber coatings, including their composition, geometry and the behavior in a broad temperature range.

Briefly, the coating effects upon the fiber attenuation can be explained as follows: upon cooling, the coating tends to shrink faster than silica glass, which results in development of an axial stress on the fiber. The developed stress is a function of the coating cross-sectional area, its coefficient of thermal expansion (CTE) and its Young's modulus; these latter values depend on the temperature significantly. On the other hand, there are forces which work against the microbending due to mechanical stiffness both of the glass and coating components.

Conversion of the coating geometry and its mechanical properties into the optical attenuation is a complicated problem. Nevertheless there are a few simple considerations which can be applied to fibers studied in this work:

- Thin coatings produce small temperature effects on the attenuation. Thus, the smallest effect is observed for the polyimide coating, with a thickness of only 15µm. In addition, the 400Å amorphous carbon layer had no effect on the microbending loss, regardless of the polymer coating used on the fiber.
- The Young's modulus and the CTE of the coatings may change drastically at phase transitions. Thermal transitions can be assessed using Differential Scanning Calorimetry (DSC). The figure below shows DSC curves obtained for the primary acrylate and the silicone coatings used in the study. The primary acrylate coating exhibits a glass transition at $T_g \approx -30°C$, while the silicone coating shows a clear melting peak at $T_m \approx -50°C$. Crystallization of the silicone is accompanied by a stepwise decrease of its volume and a significant increase of the modulus; as the thickest fiber tested, this augments the effect. Thus, indeed, the strongest thermal effect on the attenuation is produced by the silicone coating.

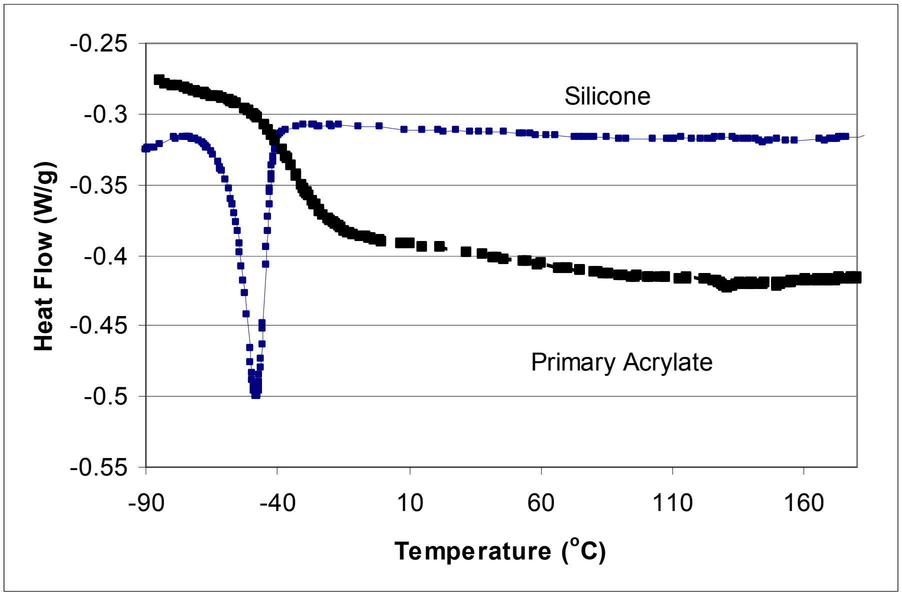

Fig. 5: Differential scanning calorimetry (DSC) scan of primary acrylate and silicone coating.

- The ETFE buffer is rigid at low temperatures. Since it does not shrink that much as the silicone, it reduces the ultimate microbending in the fiber. This is important since most optical fibers are covered with a protective jacket over the primary protective coating.

4. CONCLUSIONS

Optical fibers with various standard and specialty protective coatings were exposed to liquid nitrogen to determine their reliability at cryogenic temperatures. The tested fibers did not exhibit a drop in strength after a brief exposure at 77°K but large differences in optical transmission were observed for the different coatings. This variance in the microbending loss was attributed to the axial stress placed on the fiber depending on the coating's thickness, coefficient of thermal expansion (CTE) and the change in the Young's modulus at the cryogenic temperature.

With regard to fiber applications, the thin carbon layer has no effect on microbending loss but may be unnecessary at cryogenic temperatures since the effects of fatigue will be largely arrested at freezing temperatures when liquid water is immobilized. The polyimide coating appears to be the best choice for applications where induced loss needs to be minimized such as in distributed temperature sensing or in long-length data links. At the other extreme, the silicone coating could be employed as a simple leak detection sensor around cryogenic tanks since a silicone-coated fiber will exhibit very high microbending loss, even with an additional protective jacket. Thus, the microbending behavior of an optical fiber can be controlled based on the choice of protective coatings and buffers used in the fiber design.

ACKNOWLEDGEMENTS

The authors would like to thank Thomas Klecha and Kenneth Marceau for their technical assistance, Julie Rodriguez and Kate Shane for help with graphics, and to Brian Herbst of AFL for first proposing this research.

REFERENCES

[1] Mckenzie, I., Karafolas, N., "Fiber optic sensing in space structures: The experience of the European Space Agency," 17^{th} International Conference on Optical Fiber Sensors," SPIE Vol. 5855, 2005.

[2] Udd, E., Schulz, W., Seim, J., Morrell, M., Weaver, T., Bush, J., Adamovsky, G., "Fiber optic distributed sensing systems for harsh aerospace environments," Smart Structures and Materials, SPIE Vol. 3674, 1999.
[3] Proctor, B., et. al., "The strength of fused silica," Proc. Royal Society, A297:534-557, 1967.
[4] Kurkjian, C.R., Matthewson, M.J., *Specialty Optical Fiber Handbook*, eds., Mendez, A., Morse, T., Academic Press, p. 746, 2007.
[5] Gebizlioglu, O.S., "Time and temperature dependent material behavior and its impact on low-temperature performance of fiber optic cables," Mat. Res. Soc. Symp. Proc. Vol. 531, 1998.
[6] Kuzushita, H., et. al., "Study on transmission characteristics of UV-curable resin-coated optical fibers at low temperatures," International Wire & Cable Symposium proceedings, 1987.
[7] Lumholt, O., Bjarklev, A., et. al., "Simple fiber-optic low-temperature sensor that uses microbending loss," Optics Letters, Vol. 16, No. 17, pp. 1355-1357, 1991.
[8] King, W.W., "Thermally induced stresses in an optical-fiber coating," J. Lightwave Tech., Vol. 9, No. 8, pp. 952-953, 1991.
[9] Shiue, S.-T., Lee, S., "Thermal stresses in double-coated optical fibers at low temperature," J. Appl. Phys., Vol. 72, No. 1, pp. 18-23, 1992.
[10] Cocchini, F., "Double coated optical fibers undergoing temperature variations: the influence of the mechanical behavior on the added transmission losses," Polymer Eng. Sci., Vol. 34, No. 5, pp. 414-419, 1994.
[11] Chen, U.-C., Chang, W.-J., "Thermally induced optical effects in double-coated optical fibers by viscoelastic theory," Opt. Eng., Vol. 41, No. 6, pp. 1317-1323, 2002.