

# Reliability of Optical Fibers in a Cryogenic Environment

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**Abstract:** *Optical fibers with various protective coatings were submerged in liquid nitrogen to 77°K then tested for mechanical and optical reliability. While all the fibers maintained strength after low-temperature exposure, the optical response varied depending on the protective coating.*

## 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. In addition, applications for fibers in the cryogenic temperature range may be found in the industrial, medical, and geophysical markets.<sup>1-3</sup>

Although strength retention is an important issue, 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. 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. 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. A fiber design 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.

## Experimental setup

For mechanical and optical reliability testing, 50 $\mu$ m core/125 $\mu$ m 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:

- 50/125+ 190/245 $\mu$ m UV-curable acrylate coating
- 50/125+ 400Å hermetic carbon + 190/245 acrylate
- 50/125+ 155 $\mu$ m thermal-cure polyimide
- 50/125+ 400Å hermetic carbon + 155 $\mu$ m polyimide
- 50/125+ 450 $\mu$ m thermal-cure silicone
- 50/125+ 400Å hermetic carbon + 450 $\mu$ m 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 (see Figure 1). 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.



Figure 1: Optical fiber submerged in liquid nitrogen.

For the optical test, 100-meter fiber samples were prepared into loose coils about 6" in diameter and held together with wire ties. A 50 $\mu$ m 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). 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. 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.

## Experimental results

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, no degradation in strength was noted after the five-minute soak test.

The optical transmission tests, however, 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 900 $\mu$ m layer of ethylene tetrafluoroethylene (ETFE) buffer. (See Table 1 and Figure 2)

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

Table 1: Optical loss of fibers in LN<sub>2</sub>.

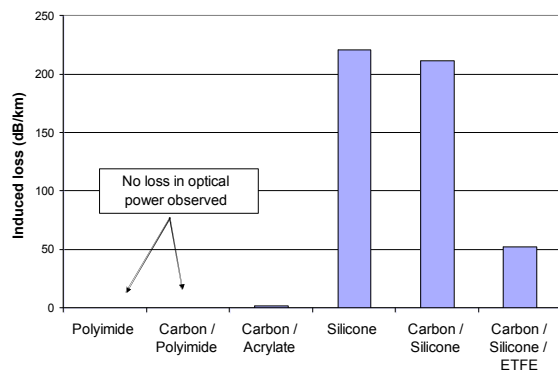


Figure 2: Optical response of fiber in LN<sub>2</sub>.

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.

## Discussion

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-section 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. There are a few simple considerations which can be applied to fibers studied in this work: (i) Thin coatings produce small temperature effects on the attenuation. Thus, the smallest effect is observed for the polyimide coating, with a thickness of only 15 $\mu$ m. In addition, the 400Å amorphous carbon layer had no effect on the microbending loss, regardless of the polymer coating used on the fiber. (ii) The Young's modulus and the CTE of the coatings may change drastically at phase transitions. The primary acrylate coating exhibits a glass transition at  $T_g \approx -30^\circ\text{C}$ , while the silicone coating shows a melting peak at  $T_m \approx -50^\circ\text{C}$ . Partial crystallization of the silicone is accompanied by a stepwise decrease of its volume and a significant increase of the modulus. Thus, indeed, the strongest thermal effect on the attenuation is produced by the silicone coating. (iii) The ETFE buffer is rigid at low temperatures. Since it does not shrink as 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.

## Conclusions

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. 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 exhibits very high microbending loss. 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.

## References

1. I. McKenzie et al SPIE, Vol. 5855, 2005, p. 262.
2. O. Lumholt et al Optic Lett., Vol.16, 1991, p 1355.
3. H. Kuzushita et al, IWCS proc., 1987, p.217.