Space Flight Heritage of Optical Fiber Cables

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Space Flight Heritage of Optical Fiber Cables

W. L. Gore & Associates

- Founded in 1958
- First products were high performance PTFE-insulated cables
- 1969 – Gore cable deployed on surface of the moon during Apollo 11 mission
- Today, a leading manufacturer of cable and cable assemblies for the space community consisting of the following product categories:
  - ESA-qualified electrical cable and cable assemblies
  - Microwave cable assemblies
  - Fiber optic cable & cable assemblies
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10+ years of Optical Cables in Space

- Space Shuttle
- Mercury Laser Altimeter (MLA)
- Geoscience Laser Altimeter System (GLAS)
- Classified Satellite Programs (multiple)

- Replacing heavier electrical wiring -or-
- Allows new design + performance possibilities
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Challenges to Fiber Optic Implementation

- Temperature extremes
- Outgassing
- Radiation
- Mechanical shock & vibration

Simplex fiber optic cables assemblies are being used today in satellites
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Glass Coating Options

<table>
<thead>
<tr>
<th>Units</th>
<th>Acrylate Coating</th>
<th>High Temperature Acrylate Coating</th>
<th>Silicone</th>
<th>Polyimide Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Service Temp. °C</td>
<td>85</td>
<td>125</td>
<td>200</td>
<td>300+</td>
</tr>
</tbody>
</table>

Buffer & Jacket Ratings

<table>
<thead>
<tr>
<th>Units</th>
<th>Hytrel®</th>
<th>Tefzel®</th>
<th>FEP</th>
<th>PFA</th>
<th>PTFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Service Temp. °C</td>
<td>135 – 180</td>
<td>180</td>
<td>204</td>
<td>260</td>
<td>260</td>
</tr>
</tbody>
</table>
Microbending in Optical Fibers

- Microbending loss in optical fibers is the loss of optical power from guided modes to lossy modes which dissipate the energy from the core of the fiber.
- Prior to development of optical fibers, microbend loss was already established in the optical waveguide community.
- In the early 1970’s, microbending loss in optical fibers was being explored and reported in the literature.
- Hanson et al. (1980) concisely combined modal coupling theory and thermo-mechanical analysis into a general loss model for temperature-dependent microbend loss.
Microbending Loss

- Microbends are typically nanometer displacements of the fiber axis correlated over millimeter lengths.
- Loss is due to the coupling of light from high order modes to “lossy” modes.

Total Internal Reflection occurs for rays which travel at an angle (relative to the core/cladding interface) which is less than the critical angle, $\theta_{\text{critical}}$. 
Microbending

Coating and Buffer Eccentricity plays an important role:

aspect ratio 1:1,000,000
(not to scale)
Hanson Model of Thermally-Induced Loss

Induced loss (in dB/km) below the equilibrium temperature, $T_0$, is given by

$$\gamma = 4.506 \times 10^7 (\alpha_3 \Delta T)^2 \frac{e^2 (\delta \beta_0)}{\delta k} \left( \frac{E_3 E_2}{(b_2 - b_1)E_1^2} \right)^2 \left( \frac{a}{b_1} \right)^8 \frac{c}{b_1^2 \Delta^5}$$

where:

- $\alpha_3$ = CTE of buffer
- $\Delta T$ = temperature difference
- $e(\delta \beta_0)$ = eccentricity
- $E_1, E_2, E_3$ = fiber, coating, and buffer moduli
- $b_1, b_2$ = radius of fiber, coating
- $a$ = core radius
- $c$ = index gradient factor
- $\Delta$ = normalized refractive index difference
- $\delta k$ = width of Fourier transform of the power spectrum of the fiber curvature

- The model does not account for the effect of shrinkage
- It was not developed for single-mode constructions, and therefore must be modified to do so.

If we wish to use Hanson’s model without further modification, then we would expect that if we plot induced attenuation vs. temperature, then we should be able to fit the data below $T_0$ with the equation:

$$Y = A + B(T_0 - T)^2$$
Mechanisms of Thermally-Induced Microbend Loss

- Thermal Expansion/Contraction
  - Polymer CTE’s are typically 10-1000x that of glass.
  - CTE difference leads to compression of optical fiber at low temperatures.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Effective Compressive Force (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide-coated fiber/PEEK</td>
<td>2.01</td>
</tr>
<tr>
<td>Polyimide-coated fiber/ePTFE/FEP</td>
<td>1.31</td>
</tr>
<tr>
<td>Acrylate-coated fiber/FEP</td>
<td>1.08</td>
</tr>
<tr>
<td>Acrylate-coated fiber/ePTFE/Polyurethane</td>
<td>0.05</td>
</tr>
</tbody>
</table>

- Shrinkage
  - At higher temperatures, polymer chain mobility increases. This allows relaxation of internal stress and frozen strains.
  - If a polymeric buffer is maintained at a temperature near or above its glass transition temperature, stress relaxation will occur. For axially stressed layers (such as extruded buffers), axially shrinkage will occur. This will tend to increase the compressive force that the fiber experiences.
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Coefficient of Thermal Expansion (per °C)

- Glass Optical Fiber
- PEEK
- Polyimide
- PTFE
- FEP
- NA951-080
- LDPE
- 2103-70A Polyurethane

Modulus (psi)

- 800 °C
- 201-300 °C
- 151-200 °C
- 101-150 °C
- 81-100 °C
- ≤ 80°C

CTE * MOD = 1
CTE * MOD = 10
CTE * MOD = 100
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Mechanisms of Thermally-Induced Microbend Loss

- All Gore designs incorporate a layer of ePTFE directly over the coated fiber.
- ePTFE buffer is an open cell structure, 75% air and 25% PTFE.
- This layer does not influence the effect of the primary coating (acrylate, polyimide, etc.) on the fiber – typically 60 µm thick.
- This layer does significantly mitigate the CTE effects of all other layers e.g. braids and cable jackets – typically 100 – 250 µm thick.
- Microbend sensitivity of any particular cable depends on factors such as:
  - Single-mode vs. multimode
  - Core size
  - Numerical aperture
  - Operational temperature range
  - Wavelength
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Mechanisms of Thermally-Induced Microbend Loss

Tight Tube Buffer

Short term - higher optical attenuation
Long term - may promote crack growth in fiber
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Mechanisms of Thermally-Induced Microbend Loss

ePTFE Buffer

25 C

-55 C
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OPTICAL POWER OUTPUT AFTER THERMAL CYCLING
2 VARIETIES of 62.5 µm optical cable

Data courtesy NASA (Ott, 1998)

-30° C to +140° C
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1.2 mm Cable

Only single-mode fiber optic cable qualified for space flight use

IAW SAE Aerospace Standard AS5382/3

A - Optical Fiber
B - Expanded PTFE buffer
C - Fluoropolymer jacket
D - Aramid braid
E - Fluoropolymer jacket
Outgassing

All materials meet ASTM E595 requirements:
TML < 1.0%
CVCM < 0.1%

Mechanical Shock & Vibration

Cable tested in qualification to:
15 - 40 g’s vibration $\Delta < .05$ dB/50 m
launch shock $\Delta < .05$ dB/50 m
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Radiation

Fiber selection is critical
Many studies in the literature
Main factors are:
  • glass dopants
  • operational wavelength
All other cable materials will survive > 10 MRad $\gamma$ radiation
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**Ribbon Cable**

- Array of 12 fibers
- Has been characterized for space flight usage
- Meets same requirements as simplex cable
- Scheduled for deployment in space in 2006
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Conclusion

• Space environments require specialized fiber optic cables for reliable performance.

• Due to the wide operational temperature ranges in space, thermally-induced microbending is a real phenomenon to be managed.

• An expanded PTFE buffering system can minimize microbend-induced attenuation changes.

• Other environmental issues such as outgassing and radiation may be managed with careful selection of optical fiber type and other materials.

• Fiber optic cable & cable assemblies have been deployed in space and are performing reliably.