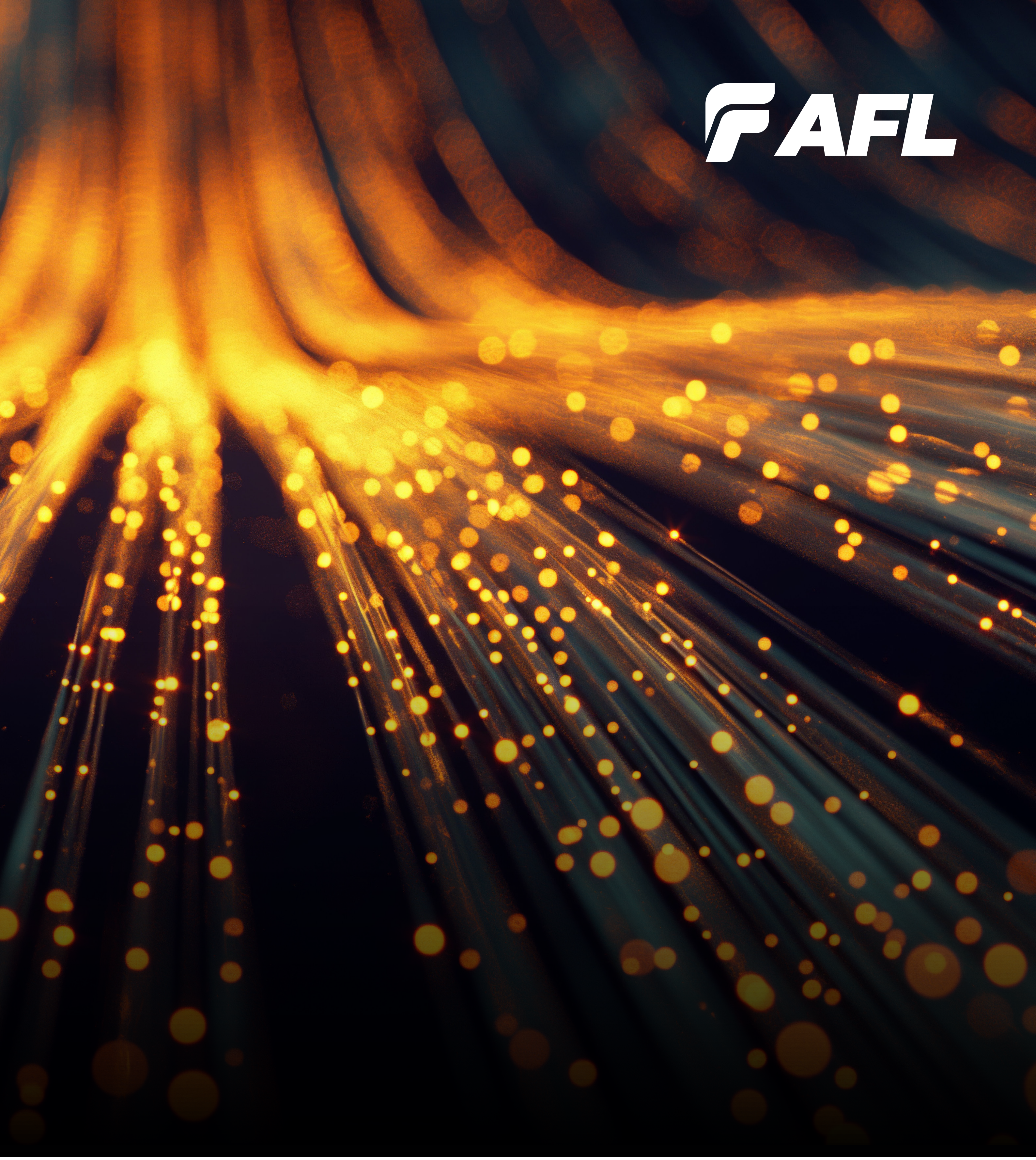

Microbending Loss in Single-Mode Fiber for Hyperscale and AI Data Centers

Introduction

This white paper explores the real-world impact of microbending in fiber network deployments, emphasizing why industry-leading management of this phenomenon enables the densest, ultra-high count fiber cable. The paper highlights key factors influencing bending sensitivity, enhancing reader awareness of the techniques and considerations for mitigating bending-related signal loss. Although measuring microbend loss in the field is not practical, understanding microbending's impact on cable performance is crucial for data center efficiency. The paper also explains why AFL's SpiderWeb Ribbon® (SWR), enabled by SR15E fiber, is perhaps the optimum building block for ultra-high density cable solutions, such as Wrapping Tube Cable (WTC) for hyperscale and AI data center applications. By expanding on this topic, the paper seeks to empower more effective decision-making for AI network designers, installers, and consultants.

Macrobending refers to signal loss from visible fiber bends with radii a few millimeters and larger. Microbending is less well known and results from microscopic pressure points or distortions, often invisible, yet capable of scattering light and degrading signal quality. This paper explains the underlying causes of microbending, identifies the factors that influence fiber sensitivity, and shows how advanced fiber design and cable architecture can mitigate their effects.

Modern, low-bend-loss Single-Mode Fibers (SMF; e.g., ITU-T G.657.A1/A2), controlled Mode Field Diameters (MFD), dual-layer fiber coatings, and high-density cable formats like Wrapping Tube Cable (WTC) with SpiderWeb Ribbon® (SWR) play critical roles in suppressing bend-induced loss. The paper concludes with real-world implications for cable selection, installation practice, and long-term network performance.

This white paper continues our series aimed at clarifying the technical nuances of deploying single-mode optical fiber in modern, large-scale data centers. These environments include enterprise, colocation, hyperscale, and AI-specific infrastructures.

For more information, please download parts one and two of this series:

- Single Mode Fiber Bend Requirements in the Data Center
- Understanding Mode Field Diameter (MFD) in Hyperscale and AI Data Centers

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What Are Macrobending and Microbending?

Macrobending

Macrobending occurs when fiber is bent in a visible curve. This deformation causes light to leak from the core into the cladding, leading to attenuation. The longer the wavelength and the larger the MFD, the greater the loss.

Typical macrobending loss at 1310 nm and 1550 nm
(extract from Single Mode Fiber Bend Requirements in the Data Center)

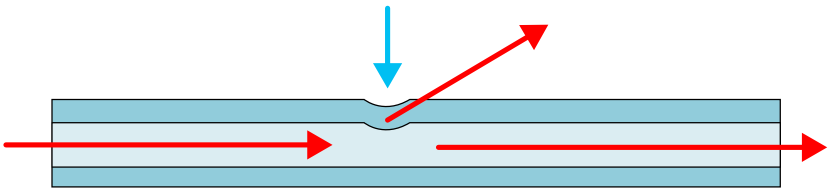
		A1 (R10)	A2 (R7.5)	B3 (R5)
Competitor A (9.2 µm)	1310 nm	**0.01 dB**	**0.03 dB**	**0.78 dB**
	1550 nm	**0.07 dB**	**0.84 dB**	**6.88 dB**
Competitor B (9.2 µm)	1310 nm	**0.02 dB**	**0.16 dB**	**1.17 dB**
	1550 nm	**0.29 dB**	**1.09 dB**	**9.4 dB**
AFL/FJK SR15E (8.6 µm)	1310 nm	**0 dB**	**0.01 dB**	**0.14 dB**
	1550 nm	**0.01 dB**	**0.23 dB**	**2.19 dB**

Macrobending is an effect on the bare fiber (as opposed to cabled fiber) as specified in the ITU-T G.657 standard.

As large data center fabric and DCI connections operate at 1310 nm, we will focus on this wavelength in considering bend performance of optical fibers and cables in hyperscale and AI data centers.

Microbending

Microbending results from microscopic perturbations in the fiber axis. These are typically caused by mechanical pressure from surrounding materials, temperature-induced contraction, or uneven surfaces in cable design. Although not visible, these deformations can scatter light, especially in loosely confined modes, increasing attenuation.



Microbend loss – guided light is scattered at micro deformation and lost into the cladding

Critically, microbending is an effect on "cabled fiber" and is not addressed in any of the ITU-T specifications. Cabled fiber can refer to any fiber in a cable from a simplex (single fiber) patch cord all the way up to the highest fiber density cables such as the Fujikura / AFL 6,912 fiber WTC.

Microbending is particularly critical in ultra-high density cables where fibers are tightly packed and mechanical and environmental pressures are more difficult to manage.

Factors Influencing Bending Sensitivity in Optical Fiber

Optical Fiber Design

- Macrobending loss is heavily wavelength dependent and negligible in the O Band, around 1310 nm for data center networks.
- Bend loss can be minimized by choosing a nominal MFD at the low end of the standards' allowed range and manufacturing to a tighter than required MFD tolerance.
- Trench-assisted or depressed cladding designs (e.g., G.657.A2) have little benefit in the data center environment at 1310 nm. However, these solutions can reduce bend loss at the higher wavelengths, such as at 1550 nm for Fiber-to-the-Home networks or 1625 nm for long haul networks.

Mode Field Diameter (MFD)

The MFD of a fiber is somewhat larger than the physical core, increasing at longer wavelengths and decreasing when the refractive index difference of the core and the cladding increases. For example, a fiber with a core diameter of 8 µm could have an MFD of 8.6 µm at 1310 nm and 9.6 µm at 1550 nm.

MFD directly influences several key optical properties:

Bend Sensitivity

Larger MFD fibers are more sensitive to bending losses. This increased sensitivity increases directly with wavelength.

Attenuation / Insertion Loss

Larger MFD fibers typically have slightly lower attenuation per kilometer – critical for long haul networks (not so relevant for short reach links inside a modern data center). Additionally, a small amount of optical power can be lost when splicing or connecting fibers with different MFDs. This loss is negligible for fibers conforming to the ITU-T G.652 standards.

Testing Implications

MFD differences can influence Optical Time Domain Reflectometer (OTDR) measurements, yielding false or misleading increases in light power levels, referred to as "Gainers", and conversely erroneous decreases in light power levels, referred to as "Excess Losses".

For greater detail on MFD, please see the second paper in this series:
Understanding Mode Field Diameter (MFD) in Hyperscale and AI Data Centers

Fiber Coating Systems

As part of the fiber drawing process, the pure glass fiber (with a diameter of 125 µm) is coated with two layers of an acrylate polymer, bringing the finished coated fiber, commonly known as "bare fiber" (the final product of the fiber manufacturing process), diameter up to 245 µm. The two layers are of a differing composition, providing specific properties and serving different purposes for the fiber.

A final layer is commonly added to give the fiber its designated colour, ultimately bringing the diameter of the bare fiber up to 250 µm.

Microbending performance in optical fibers is significantly influenced by the mechanical properties of these dual-layer coatings, particularly the balance between the inner primary and outer primary layers.

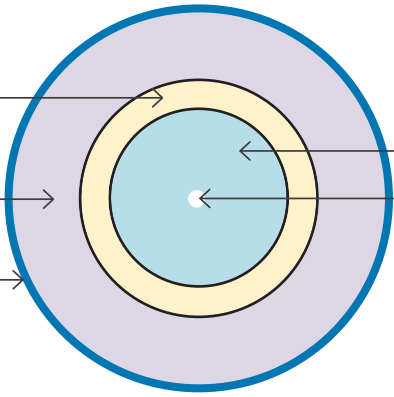
Inner Primary Coatings – Soft Coating for Cushioning and Stress Reduction

The inner primary coating, which is in direct contact with the glass fiber, is designed to be a soft cushioning layer (a low Young's modulus - a measure of a material's stiffness or elasticity). This softness allows it to absorb and cushion external stresses, such as lateral pressures from neighbouring fibers or other cable elements or temperature-induced contractions.

Experimental studies show that reducing the modulus of the primary coating significantly decreases microbend-induced attenuation. For instance, fibers with low-modulus coatings exhibit up to 50% lower attenuation compared to high-modulus coatings under similar conditions.

The primary coating must remain elastic across the full design temperature range of the cable. It is this elasticity of the coating that prevents brittleness and maintains the stress absorption capabilities of the fiber.

By optimizing the balance of softness and elasticity of the inner coating, the microbend performance can be maximized while still protecting the fiber across the full temperature range from -10°C to +60°C (indoor) and -40°C to +70/75°C (outdoor).



Outer Primary Coatings - Hard Outer for Structural Support and Mechanical Durability

The outer coating is harder and provides mechanical durability. It protects the glass and the inner coating from physical damage during handling, cabling, and installation. Its rigidity ensures that the inner coating retains its stress-relieving properties without being compressed or deformed under external forces.

It is this outer coating that gives optical fibers their handleability and robustness, often surprising to people when they think they are handling an extremely fine thread of pure glass (without the coatings, the glass strand is far more brittle and sensitive to handling and bending).

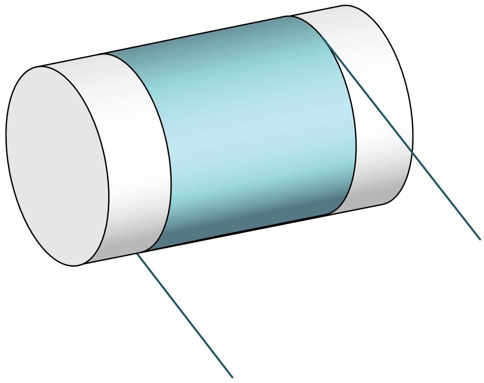
In ultra-high density cable design, a critical function of the outer coating is to provide a low friction outer layer to enable movement of fibers relative to each other inside the tightly packed cable. In these cables, when the cable routes and bends around a corner, the fibers need to be able to move relative to each other inside the cable jacket. A well-designed fiber coating will have a silky-smooth feeling to the touch, allowing this low friction movement in a tightly packed bundle.

The coating interface between the inner and outer coatings is a critical design feature and ensures that stress is not transmitted from the outer layer to the inner layer or ultimately to the glass itself. Proper adhesion between the coatings prevents delamination, which could compromise stress absorption and lead to increased microbending losses.

This balance between softness and rigidity is critical for maintaining optical performance in tightly packed, high-density cables under varying environmental and physical conditions.

Testing Microbend Performance

The microbend performance of optical fiber is evaluated following IEC TR 6221:2012 – Optical Fibers – Measurement methods – Microbending sensitivity. Four testing methods are outlined and for testing microbending performance in optical fiber ribbons, Method B is recommended.

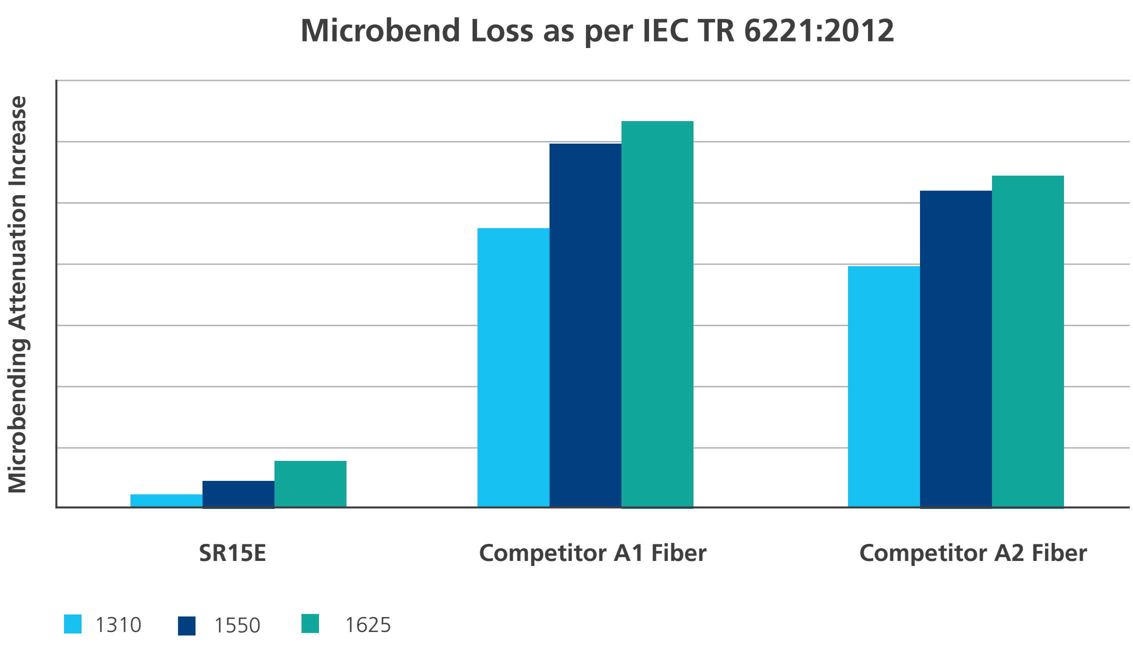


Microbend test: 400 meters of fibre wrapped in a single layer around an abrasive coated 200 mm diameter quartz drum

Method B involves wrapping 400 m of either a single optical fiber or a single optical fiber ribbon around a fixed diameter drum covered with abrasive paper (typically 40 µm AL_2O_3). The minimum diameter of the drum is 200 mm (so as not to induce any macrobending) and the drum should be constructed of a low thermal expansion material such as quartz.

The fiber/ribbon is wound onto the drum in a single layer (avoiding crossovers) with a controlled winding tension. The attenuation is measured when fully wound, giving the fiber attenuation plus the increase due to microbending induced from the rough surface of the abrasive paper. The fiber is then released from the drum and laid in loose coils and the attenuation measured again, yielding the pure fiber attenuation which can be subtracted from the coiled measurement to give the increase due to Microbending.

The results from testing Fujikura SR15E and commonly found competitor G.657.A1 and G.657.A2 fibers are shown below.



High-Density Cable Design and Bending Challenges

Why Density Drives Bend Sensitivity

Fiber Packing Ratios

The foundation of high-density cable design lies in the cable construction and the fiber packing ratio. The fiber packing ratio refers to the proportion of the optical fiber cross-sectional area relative to the overall cable cross-sectional area. A higher ratio indicates a greater optical fiber density within the cable.

Contact Pressure Between Elements and/or Subunits

In high-density cables, the increased optical fiber density leads to greater contact pressure between elements or subunits (e.g., ribbons or loose tubes). Excessive pressure can cause physical deformation of the fibers, resulting in microbending and optical loss. Since contact pressure is influenced by cable bending, temperature fluctuations, and external forces causing expansion or contraction of the cable or elements of the cable, the selection of cable materials and fiber coating design becomes critical.

Spatial Constraints in Ducts and Trays

Densely packed cables must fit within the limited spaces of ducts and wiring trays. These spatial constraints impose limitations on the outer diameter of the optical cable, which is determined by the fiber structure and the fiber packing ratio.

Cable Construction Methods

Traditional Gel-Filled Cables

Gel-filled loose tube cables have long served as a standard structure in the optical fiber cable market, offering reliable protection in diverse deployment environments. However, as the number of fibers needed in modern high density AI networks increases, this traditional construction reveals several limitations:

Large Overall Cable Outside Diameter (OD)

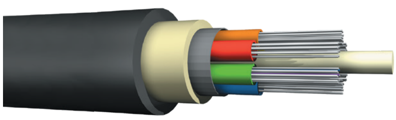
The fibers are routed, loosely in a nylon/plastic tube filled with gel to offer the fibers more cushioning and protection. The individual tubes, typically holding 12 or 24 fibers, are then layered up inside the outer cable jacket. The combination of the tubes, the gel, and the interstices between the tubes all result in a very low fiber packing density.

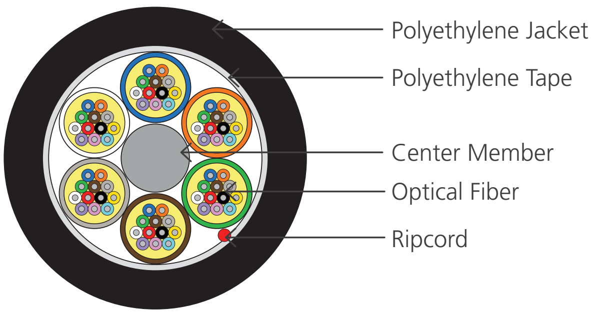
Preparation Time

The gel used in traditional cable designs is an oil-based gel and takes a significant amount of time to remove from each individual fiber prior to splicing or connectorizing.

Splicing Time

Traditional gel-filled cables deploy individual fibers which must be spliced individually. Modern ribbon-based cables deploy 12 or 16 fiber ribbons, which can be mass fusion spliced (spliced ribbon to ribbon), greatly reducing the splicing time of Ultra-High Fiber Count (UHFC) cables.





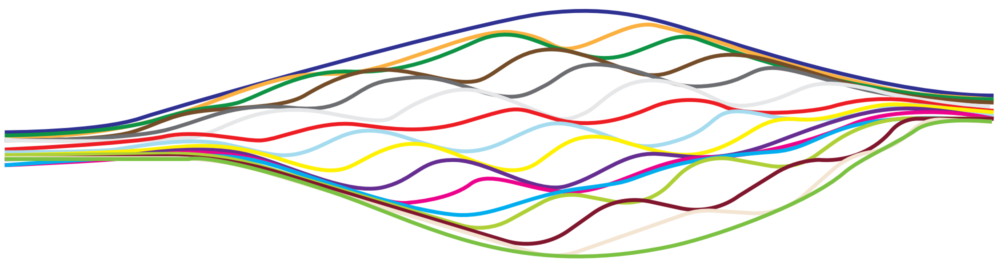
Dry Loose Tube Designs

Dry loose tube designs eliminate the need for gel, thereby removing the associated cleaning step during installation and significantly improving workability in the field. These designs achieve water-blocking performance using water-swellable yarns and tapes, which effectively protect the fibers without the mess of gel. However, one trade-off is that incorporating these dry water-blocking elements may result in a larger overall cable diameter compared to conventional gel-filled designs, thereby further reducing the fiber packing density.

Limitations of Traditional Hard Ribbon Cable Designs

Ribbon cables are essential for improving installation efficiency, particularly in high-fiber-count networks, as they allow for mass fusion splicing. However, traditional encapsulated or hard ribbon structures have inherent bend directionality, meaning they can easily bend up and down but not side to side. When cables with traditional ribbons are routed through bends, internal fiber strain can become a concern. To mitigate this risk, sufficient space must be reserved within the cable or its subunits to allow the ribbons to move and adjust freely during bending. This requirement imposes design limitations, resulting in vlower fiber packing densities than ribbon cables with flexible ribbons.

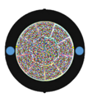
Spider Web Ribbon (SWR®) and Wrapping Tube Cable (WTC)



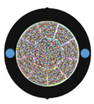
16F SWR

SWR consists of multiple optical fibers intermittently bonded into a ribbon structure. This configuration allows for high flexibility of the ribbon structure, allowing the fibers to collapse onto each other or "roll" together, giving the general term of rollable ribbons. This eliminates bend directionality, enabling the ribbon to bend and route in all directions, like a bundle of individual fibers.

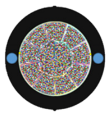
Available in 12 and 16-fiber ribbons (SWR12 & SWR16), the fibers can be mass fusion spliced, ribbon to ribbon, greatly reducing installation time and costs.



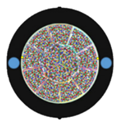
Indoor/Outdoor WTC
144 fiber; 12.5mm OD



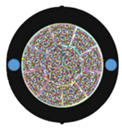
Indoor/Outdoor WTC
288 fiber; 13mm OD



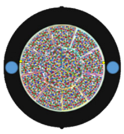
Indoor/Outdoor WTC
432 fiber; 14mm OD



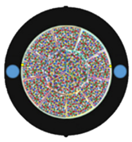
Indoor/Outdoor WTC
576 fiber; 15mm OD



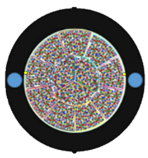
Indoor/Outdoor WTC
864 fiber; 16.5mm OD



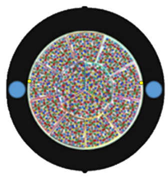
Indoor/Outdoor WTC
1152 fiber; 17.5mm OD



Indoor/Outdoor WTC
1,728 fiber; 21mm OD



Indoor/Outdoor WTC
3,456 fiber; 25.5mm OD



Indoor/Outdoor WTC
6,912 fiber; 31mm OD

Advantages of WTC in Density and Routing

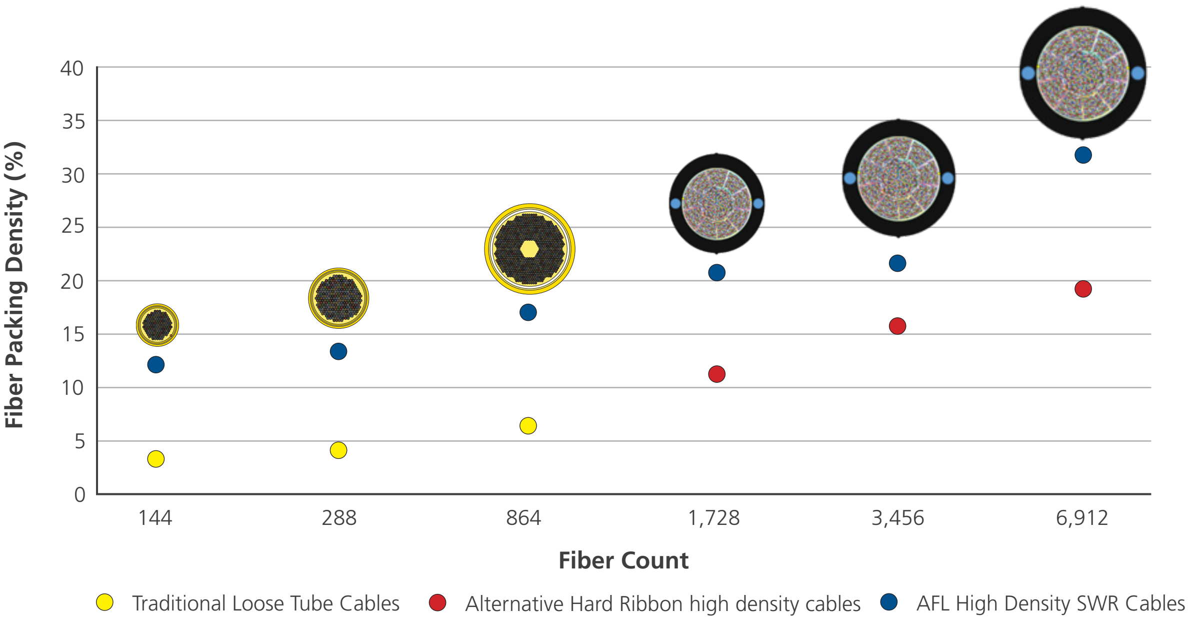
Compared to traditional optical cables, WTC offers an exceptionally high packing ratio and, consequently, a significantly smaller outer diameter. This enables easier cable handling during installation, particularly in space-constrained environments. Its compact and flexible design facilitates deployment through narrow ducts and complex routing paths, making it increasingly popular in urban infrastructures and data center applications. Additionally, the adoption of a dry construction further simplifies field installation work, resulting in reduced installation time and cost.

WTC's Superior Fiber Density and the Microbend Implications

While WTC offers superior Fiber density over conventional cable designs, this increased density may elevate the risk of microbend losses. To mitigate these risks, optimized fiber design and cable structure are essential – particularly with respect to minimizing contact pressure between fibers. A well-balanced design approach is necessary to maintain high density without compromising optical performance.

Fiber Density (FD) is a term that has emerged with the adoption of UHFC cables - cables with fiber counts greater than 576f, currently all the way up to 6,912 fibers. The FD is the combined cross section of all the fibers in the cable as a ratio to the overall cross sectional area within the Outside Diameter (OD).

Over the years, fiber packing density has increased from about 3% for a traditional Loose Tube 144f cable to 13% for a High Density Ribbon 288f cable.



Cable	Fiber Count	Packaging Density
Loose Tube	144	2.94%
Ruggedized MicroCore	144	12.46%
Loose Tube	288	3.89%
Ruggedized MicroCore	288	12.76%
Ruggedized MicroCore	576	14.98%
Loose Tube	864	6.42%
Ruggedized MicroCore	864	16.90%
Wrapping Tube Cable	1,728	20.20%
Hard Ribbon Cable	1,728	11.06%
Wrapping Tube Cable	3,456	21.26%
Hard Ribbon Cable	3,456	16.44%
Wrapping Tube Cable	6,912	31.13%
Hard Ribbon Cable	6,912	18.85%

Environmental Effects on Bending Performance

Temperature cycling significantly impacts optical fiber performance in high-density cables due to the varied expansion and contraction rates of cable materials. Components such as outer jackets, buffer tubes, and silica glass fibers each have different Coefficients of Thermal Expansion (CTE). These differences lead to mechanical stresses and increased attenuation from microbending.

Thermal Expansion and Microbending

- Outer jackets and buffer tubes typically expand and contract more than silica fibers.
- Temperature changes induce longitudinal and radial forces, affecting tightly packed fibers.
- Forces cause microscopic pressure points (microbends), scattering light and increasing signal loss, particularly at longer wavelengths like 1550 nm.

Impact of High-Density Cable Design

In densely packed cables, limited internal space exacerbates thermal stress effects. During colder conditions, cable contraction increases internal pressure, causing:

- Fiber-to-fiber contact.
- Increased microbending losses.
- Greater vulnerability in constrained installations (ducts, trays, tight bends).

Strategies to Mitigate Microbending

Effective cable design incorporates strategies to minimize microbending:

Optimized Dual-Layer Fiber Coatings

- Inner primary coating: Low modulus material cushions stress, maintaining elasticity across operational temperatures (-40°C to +70°C).
- Outer primary coating: Provides structural support and low-friction surface, enabling fiber movement.

Internal Slack Management

- Controlled internal slack accommodates thermal expansions and contractions, reducing localized pressures.

Environmental Qualification Testing

Rigorous testing according to industry standards (Telcordia, IEC) ensures cable reliability.
Tests include: crush, impact, tensile, flex, twist, and cold bend.

Real-World Application and Reliability

Environmental qualification confirms cable integrity across various deployment scenarios:

- Ducts and subducts: Manage tension, radial pressure, temperature fluctuations.
- Overhead trays: Resist stresses from multiple cables, bends, torsion, and sag.
- Buried environments: Handle soil movement, backfill pressure, and structural loads.

Water-Blocking Capabilities

Reliable water-blocking mechanisms prevent performance degradation from sheath damage and water ingress:

- Water-swellable yarns/tapes enhance dry cable designs, simplifying installation.

Long-Term Stability and Performance

A well-engineered cable design balances materials, internal structure, and rigorous testing, ensuring:

- Reduced microbending sensitivity across environmental extremes.
- Sustained optical performance in high-stress deployments (hyperscale, AI data centers).
- Confidence in consistent, validated performance.

Performance by Design

Microbending and macrobending are not edge cases – they are active design constraints in hyperscale networks. Most designers, installers, and end users are familiar with macrobending and take steps to manage it. Microbending is a less known source of fiber attenuation critical to the performance of the high-density cables required by advanced hyperscale and AI data centers. The performance of a cable depends not only on underlying fiber attenuation but on how the cable manages mechanical and environmental stress.

Best practice high density fiber cable design for hyperscale and AI data centers requires systematic management of bend issues, including both fiber design and cable structure:

- Excellent macrobending performance at 1310 nm – the wavelength of operation in data center applications.
- Dual-layer fiber coatings optimized for damping and temperature resilience.
- Rollable ribbon cable design (WTC with SWR) for high packing with low stress.

Together, these innovations yield a fiber, ribbon, and cable system that delivers superior optical performance in real-world, high-density environments.

Designers, installers or network owners could ask, "I can understand and directly measure macrobend attenuation – but how do I know that my cable has good microbend performance?" It is not practical to test microbend performance in the field, but microbend performance is essential to building high density fiber cables capable of meeting mechanical and thermal cycling requirements. Cable diameter is the best indicator of fiber microbend performance for high density, high fiber count cables.

Founded in 1984, AFL is an international manufacturer providing end-to-end network solutions to the energy, service provider, enterprise, hyperscale and industrial markets. The company's products are in use in over 130 countries and include fiber optic cable, assemblies, and hardware, transmission and substation accessories, outside plant equipment, connectivity, test and inspection equipment, fusion splicers, and training. AFL also offers a wide variety of services supporting data center, enterprise, wireless and outside plant applications.

Headquartered in Spartanburg, SC, AFL has operations in the U.S., Mexico, Canada, Europe, Asia and Australia, and is a wholly owned subsidiary of Fujikura Ltd. of Japan.