Understanding Mode Field Diameter (MFD) in Hyperscale and AI Data Centers

Prologue

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.

This installment focuses on Mode Field Diameter (MFD), a crucial yet often overlooked fiber characteristic that influences installation, performance, and testing methodologies. By addressing MFD and the associated implications, the paper seeks to clarify fiber's intricate properties to benefit readers of all experience levels, including designers, installers, and operators.

Applications inside the data center: MFD plays a significant role in transmission efficiency at the 1310 nm wavelength inside the data center. For more information on single-mode bend requirements in high-performance data center environments, please download part one in the series:

- Single Mode Fiber Bend Requirements in the Data Center

This series will also explore the significance of micro-bending in deploying ultra-high fiber count cables.

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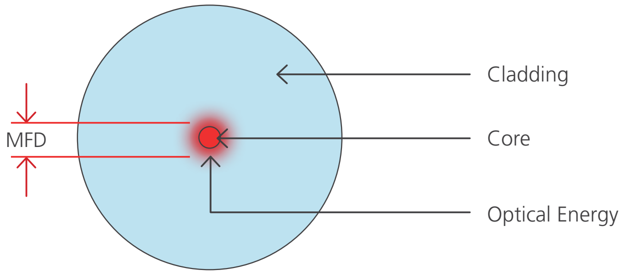
What is MFD and Why Does It Matter?

MFD represents the diameter of the area through which light propagates in a single-mode fiber.



Step index single mode optical fiber showing core in cladding structure and wavelength dependent distribution of optical energy.

Specifically, MFD is the diameter of the circle at which the optical intensity has fallen from its peak value at the center of the core to a prescribed minimum value of intensity (decreased by $1/e^2$, where e is the base of the Natural Logarithm).

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 8µm could have an MFD of 8.6µm at 1310nm and 9.6µm at 1550nm.

MFD directly influences several key optical properties:

Bend Sensitivity

Larger MFD fibers are more sensitive to bending losses. In these fibers, the light is less tightly confined, resulting in more power being carried in the lower index cladding. This leads to greater bend loss. Bend performance is highly dependent on wavelength, with greater loss at longer wavelengths.

Insertion Loss (IL)

A small amount of optical power may be lost when joining or splicing fibers with different MFDs. This loss is small for fibers conforming to the ITU-T standards listed below.

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 "Exaggerated Losses". This discrepancy arises because OTDR measurements depend on backscattered light, which is determined by the material properties of the glass and the optical intensity. A smaller MFD leads to higher intensity and increased backscatter for identical glass properties. This can result in false gain or loss indication at the joint of two fibers with different MFDs (subsequent sections cover this topic in more detail).

MFD has less impact on these properties:

Dispersion

MFD has no impact on polarization mode dispersion and has only a small influence on chromatic dispersion. Due to small values of both material and waveguide dispersion at this wavelength, chromatic dispersion is small at 1310 nm. MFD only affects waveguide dispersion.

Return Loss (RL)

MFD difference at a connection does not contribute to RL. The very small amount of power loss due to MFD difference at a joint dissipates in the cladding and not reflected.

MFD in Fiber Standards

Industry standards define allowable nominal values and tolerance ranges for MFD. Within a single supplier's product range, MFD can vary within these tolerances.

Key standards include:

- **ITU-T G.652 (Standard Single-mode Fiber)** – Typical MFD: 8.6-9.5µm ± 0.6µm.
- **ITU-T G.657 (Bend-insensitive Fiber)** – MFD: range of nominal values 8.6-9.2µm, tolerance ± 0.4µm.

Internationally, IEC 60793 2 50 is aligned with ITUT- G.652. European national standards (e.g. the EN versions of IEC 60793) also reference these criteria.

In the United States, TIA/EIA 60793 references the performance and characteristics defined by the ITU-T documents. Telcordia GR 20 sets performance requirements for optical fiber that are consistent with G.652.

Cabled fiber standards referencing G.652 include ISO/IEC 11801 and TIA/EIA 568.

MFD Mismatch: Homogeneous vs. Heterogeneous Joints

When splicing or connecting fibers with different MFDs, an MFD mismatch occurs.

This mismatch may arise from variations in the typical MFD of fiber in the following scenarios:

- A single fiber type from one manufacturer with an MFD mismatch within the allowable range of ± 0.4µm (homogeneous).
- Different fiber types from the same manufacturer, with either different nominal values or different values within the allowable range (heterogeneous).
- Different fibers from different manufacturers (heterogeneous).

Regardless of the MFD mismatch source, all mismatches across the three scenarios are standards-compliant and fully interoperable.

Quantifying IL

Whether by fusion splicing or use of separable connectors, joining two fibers with different MFDs results in inefficient coupling.

The joint insertion loss, IL, may be expressed with this formula:

$$IL = -10\log_{10}\left(4MFD_1^2 MFD_2^2/(MFD_1^2 + MFD_2^2)^2\right)$$

1. Agrawal, G. P. Fiber-Optic Communication Systems (4th ed., Wiley, 2010)
2. Keiser, G. Optical Fiber Communications (5th ed., McGraw-Hill, 2011)

MFD mismatch loss is an expression of inefficient coupling of two waveguides and does not depend on the direction of transmission. Mismatch loss is additive to other connection losses including misalignment loss and contamination loss.

Commercially available G.652.D compliant fibers are specified with a nominal MFD ranging from 8.6µm to 9.2 µm with a variance of ± 0.4µm. The table below illustrates the expected MFD mismatch loss for two spliced or connected fibers with varying MFDs, calculated with the above formula.

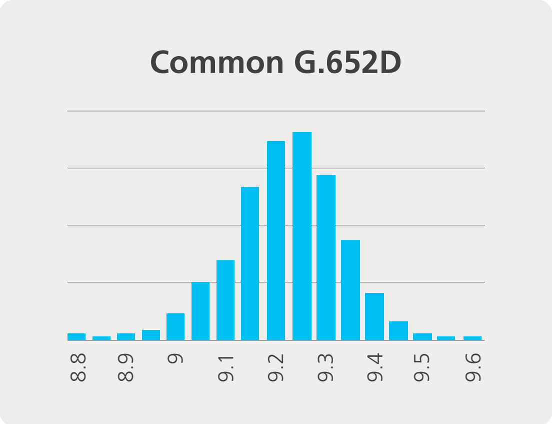
Insertion Loss (dB) Due to MFD Mismatch

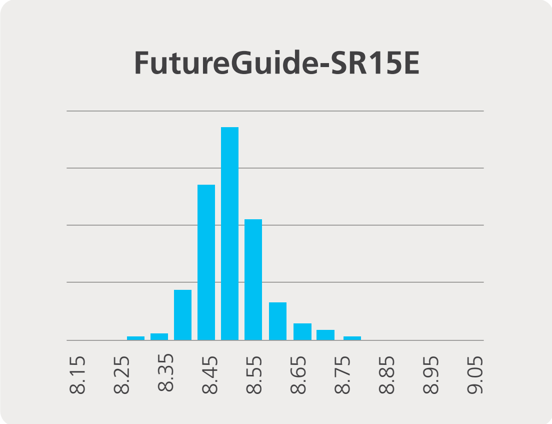
		Fiber 1 MFD														
		8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0	9.1	9.2	9.3	9.4	9.5	9.6
Fiber 2 MFD	8.2	0.000	0.001	0.003	0.006	0.010	0.015	0.022	0.029	0.038	0.047	0.057	0.069	0.081	0.094	0.107
	8.3	0.001	0.000	0.001	0.002	0.005	0.010	0.015	0.021	0.028	0.037	0.046	0.056	0.067	0.079	0.092
	8.4	0.003	0.001	0.000	0.001	0.002	0.005	0.009	0.015	0.021	0.028	0.036	0.045	0.055	0.066	0.077
	8.5	0.006	0.002	0.001	0.000	0.001	0.002	0.005	0.009	0.014	0.020	0.027	0.035	0.044	0.054	0.064
	8.6	0.010	0.005	0.002	0.001	0.000	0.001	0.002	0.005	0.009	0.014	0.020	0.026	0.034	0.043	0.052
	8.7	0.015	0.010	0.005	0.002	0.001	0.000	0.001	0.002	0.005	0.009	0.014	0.019	0.026	0.034	0.042
	8.8	0.022	0.015	0.009	0.005	0.002	0.001	0.000	0.001	0.002	0.005	0.009	0.013	0.019	0.025	0.033
	8.9	0.029	0.021	0.015	0.009	0.005	0.002	0.001	0.000	0.001	0.002	0.005	0.008	0.013	0.018	0.025
	9.0	0.038	0.028	0.021	0.014	0.009	0.005	0.002	0.001	0.000	0.001	0.002	0.005	0.008	0.013	0.018
	9.1	0.047	0.037	0.028	0.020	0.014	0.009	0.005	0.002	0.001	0.000	0.001	0.002	0.005	0.008	0.012
	9.2	0.057	0.046	0.036	0.027	0.020	0.014	0.009	0.005	0.002	0.001	0.000	0.001	0.002	0.004	0.008
	9.3	0.069	0.056	0.045	0.035	0.027	0.019	0.013	0.008	0.005	0.002	0.001	0.000	0.000	0.002	0.004
	9.4	0.081	0.067	0.055	0.044	0.034	0.026	0.019	0.013	0.008	0.005	0.002	0.000	0.000	0.000	0.002
	9.5	0.094	0.079	0.066	0.054	0.043	0.034	0.025	0.018	0.013	0.008	0.004	0.002	0.000	0.000	0.000
	9.6	0.107	0.092	0.077	0.064	0.052	0.042	0.033	0.025	0.018	0.012	0.008	0.004	0.002	0.000	0.000

The maximum IL for any possible combination of fibers is 0.107dB. The MFD range for identical fiber types is shown in the pale blue (8.6µm) and bright blue (9.2µm) boxes. For like-to-like connections, the maximum IL is 0.038dB.

What is the real-world distribution of MFD? To answer this question, we analyzed data from various fiber types, examining a sample size of tens of thousands of individual fibers.

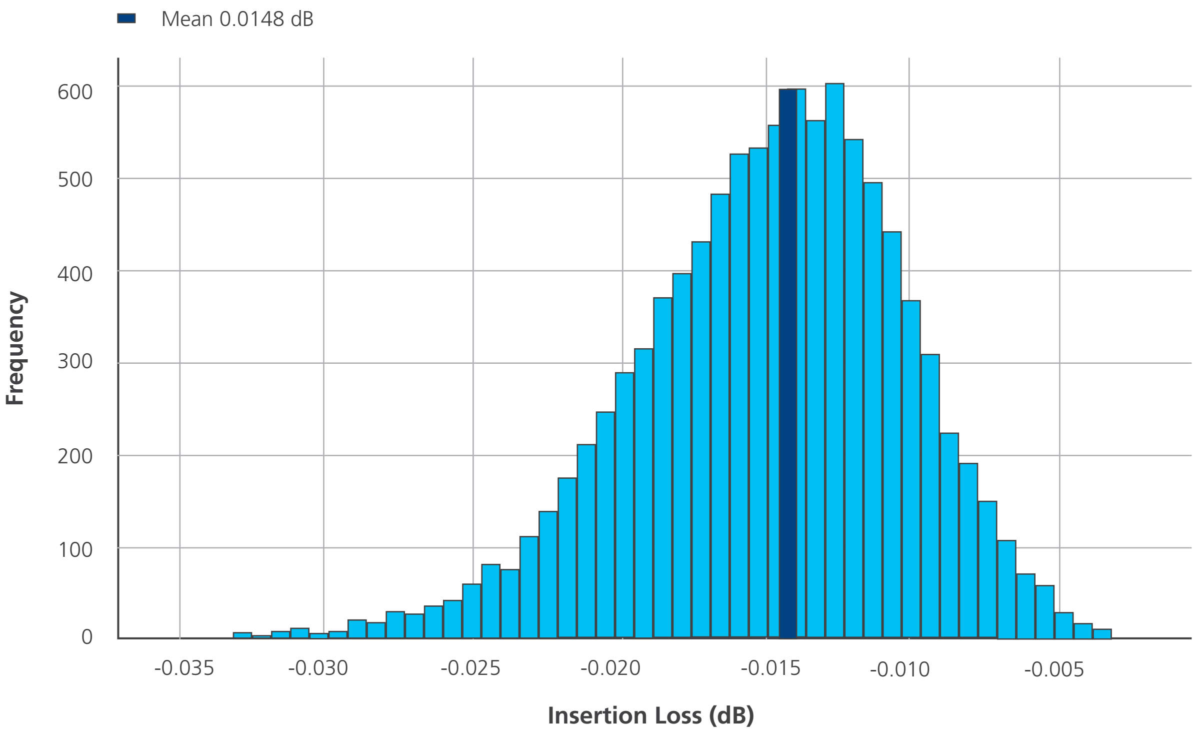
Here are the MFD distribution results we observed for two specific fiber types: a commonly used G.652D compliant fiber and a fiber manufactured by Fujikura specifically for dense, high fiber count cables, FutureGuide™ SR15E.





In both cases, MFD approximates a Gaussian distribution and does not fill the full ±0.6μm variance allowed by the specification. The distribution of MFD of SR-15E fiber is notably tight with a ±0.2μm from the Nominal value.

Using the mean and standard distribution values of these distributions, we performed a Monte Carlo simulation, randomly mating a fiber from the common G.652D distribution and another from the SR15E distribution. 10,000 connection events were simulated.



The mean IL was found to be 0.0148dB with a standard deviation of 0.0047dB. All 10,000 random events exhibited IL below 0.035dB.

MFD mismatch when splicing or connecting two fibers contributes minimally to joint insertion loss. Even when splicing or connecting identical fibers from the same manufacturer, some loss may still occur.

Introduction to OTDR Testing

An Optical Time Domain Reflectometer (OTDR) operates by sending pulses of light down a fiber and measuring reflected or backscattered light. The time taken for the reflected or backscattered light to return to the device determines the distance from which the light was reflected, based on the speed of light in glass. The amplitude of the returned pulses is processed and plotted by the OTDR to produce the "Trace", showing the channel loss versus distance, along with the relative levels of reflected light.

Rayleigh Scattering and Backscatter

Rayleigh scattering occurs when light is deflected in various directions from tiny imperfections or particles much smaller than the light's wavelength. Consider sunlight hitting a light mist or dust in the air—the light scatters, making the sky appear blue. In materials like glass, even minor variations in density or composition can cause this scattering, gently redirecting some of the light from its original path.

OTDR Measurement Uncertainty

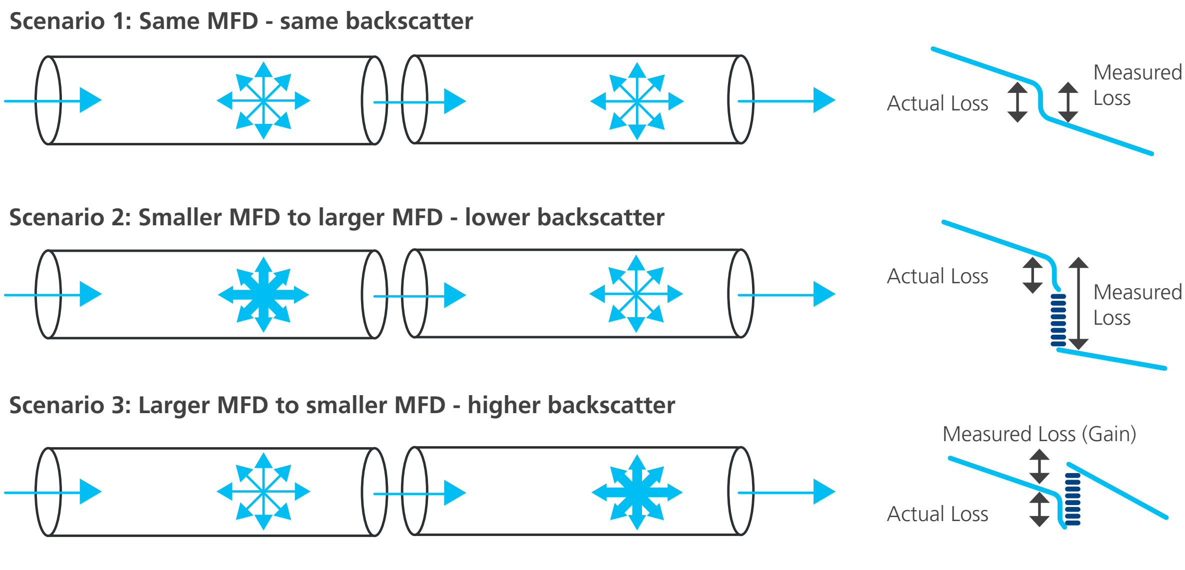


Image 1: Source - Image adapted from thefoa.org, with color modifications.

In high-quality single-mode fibers, Rayleigh scattering typically causes a loss of about 0.3 dB/km at 1310 nm and significantly contributes to total attenuation. This scattering loss represents the cumulative effect of all light scattered out of the forward-propagating mode due to microscopic density and refractive index fluctuations in the glass. Most of the scattered light enters the cladding and is lost.

However, a very small fraction of that scattered light is recoupled into the fiber's guided (backward) mode, known as Rayleigh Backscatter, or simply backscatter in this context. In practice, the fiber-coupled backscattered signal (measured by an OTDR) is typically around –70 to –80 dB (0.00001% to 0.000001% of the transmitted light) relative to the launched pulse power.

Different fibers have varying levels of backscatter depending on geometry, material composition, and glass manufacturing process.

Impact of MFD and backscatter coefficient on OTDR results

Backscatter is proportional to $1/\lambda^4$ (i.e., backscatter is proportional to the inverse of the fourth power of the wavelength). For the same material conditions, backscatter is proportional to MFD^4. (i.e., the fourth power of MFD). This is because scattering increases with the square of intensity and smaller MFD leads to higher intensity due to higher concentration of optical power.

Consider a fiber connection – splice or connector – where the second fiber has a smaller MFD, resulting in a higher backscatter (see Image 1, Scenario 3). The OTDR will interpret this increase in backscattered light as a negative "loss" across the connection because the backscatter will be stronger in the second fiber. This is commonly known as a "Gainer". Conversely, if the MFD increases, backscatter will decrease, and the OTDR will interpret the results as an increased loss, known as an "Excess Loss" (see Image 1, Scenario 2).

The practical difficulty in assessing single direction OTDR results is that a Gainer always indicates a backscatter mismatch, but a higher-than-expected loss could be due to Excess Loss from a backscatter difference or a high loss.

When using an OTDR in one direction only, it is not possible to determine the true insertion loss. If the two fibers are of a different type or manufacturer, some difference in backscatter is likely. Even when both fibers are of the same type and manufacturer, normal variations in MFD and material condition can result in a difference of backscatter.

The true loss of the joint between the fibers as measured using an OTDR can only be determined by testing in both directions. The true loss is the sum of the two results – the Gainer will offset the Excess Loss.

AFL FlexScan® FS200 SM OTDR, which can be used to show a Gainer

Rayleigh Backscatter is the phenomenon exploited for OTDR testing. However, in actual communication operation or in testing a fiber link with a light source and power meter, Rayleigh scattering levels are low and factored into the normal fiber attenuation.

When commissioning newly installed complex data center links, especially over long distances or between buildings with multiple connections and splice points, recording an OTDR trace of the channel serves as a record of the "Installed State" of the channel for future reference and troubleshooting. However, the OTDR trace should not be the definitive loss characterization of the link – an OTDR trace should always be secondary to the OLTS loss measurement.

OLTS Testing: Definitive Loss Measurement

An Optical Loss Test Set (OLTS) operates by injecting light into a fiber using an Optical Light Source (OLS) and measuring the detected light at the far end of the system with an Optical Power Meter (OPM). In most OLTS systems, the light level at the point of entry to the fiber system is referenced or zeroed, allowing the light level at the end of the system or channel to be displayed as the total loss through the system. This total loss includes the loss within the fiber and the loss from each connector pair or fusion splice.

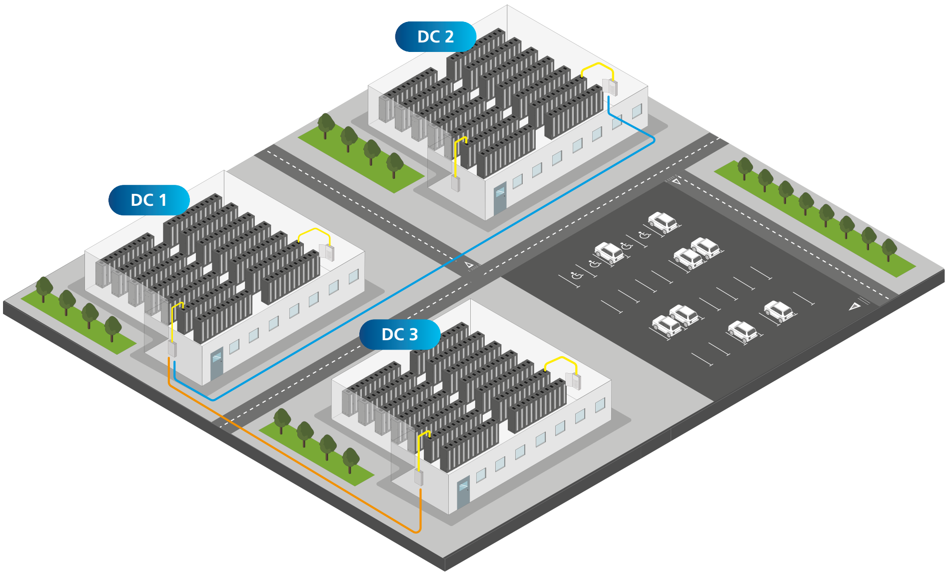


Image 2: Fiber link schematic

A fiber channel is defined as the fiber connection from one electronic device to another device, excluding the end patchcords connecting to the devices. In a data center, these devices could be servers, storage devices or switches. This channel could be a simple link across several racks in the same row of a data center or a complex Data Centre Interconnect (DCI) link between two data centers on the same campus or in the same metro area (as shown in image 2).

An MFD mismatch in a complex fiber channel can occur due to different fibers or cables being deployed in the different links. The maximum loss contributed by the MFD mismatch is calculated using the formula referenced in the section "Quantifying IL". Even in extreme cases of MFD mismatch, the contributed loss is negligible – 0.069dB. This minimal loss will be shown as part of the connector pair loss or the fusion splice loss when loss characterizing with an OLTS.

Accurate measurement of Fiber Channel Loss

To accurately measure the true loss characteristics of a fiber channel with multiple links, the most precise method is using an OLTS. For loss characterization in data center applications, this OLTS test should be conducted at 1310nm (the wavelength at which data center transmission operates) and also at 1550nm to detect any micro or macro bends that may not appear at 1310nm due the fiber's bend resilience at the lower wavelength (see the first white paper in this series: Single Mode Fiber Bend Requirements in the Data Center). The measured loss from End A of the channel and from End B will not differ sufficiently to warrant testing in both directions.

Testing Best Practices for Hyperscale and AI Data Centers

To ensure accurate fiber performance assessment, we recommend adherence to the following best practices:

Use OLTS for Characterization

- Provides a definitive, standards-based measurement of link loss, giving an indication of the operational loss of the system when live.
- Uni-directional is sufficient as differences in loss in opposite directions are insignificant and do not justify the increased testing time.
- Testing at 1310nm for "Operational Loss" and at 1550nm for micro and macro bending detection is required.
- Avoids the artifacts seen in OTDR testing.
- Sole test required by AFL for issuance of the fiber system warranty.

Use OTDR for Visual Mapping & Troubleshooting

- Provides a clear visualization of link continuity and connector/splice locations, flagging any inconsistencies or excessive bends in the cable route.
- When testing unidirectionally, the pass/fail criteria should be set to the total link loss budget (and not individual connector or splice losses)
- Should not be used as the primary method for loss characterization.
- If OLTS is unavailable, bi-directional OTDR testing is required to reduce backscatter coefficient discrepancies.

Conclusion: Clarity on MFD's Role in Fiber Deployments

For hyperscale and AI-driven data centers, MFD is a manageable characteristic that contributes a negligible level of loss and should be understood but not overemphasized in performance concerns.

Key takeaways:

Importance of MFD

MFD is crucial for transmission efficiency, especially at the 1310 nm wavelength. MFD influences insertion loss, bend sensitivity, and testing methodologies.

MFD and Optical Properties

MFD mismatch IL represent the small power loss that occurs when joining fibers with different MFDs. Larger MFD fibers are more sensitive to bending losses. However, MFD affects insertion loss minimally and has no impact on return loss or dispersion.

Industry Standards

Standards like ITU-T G.652 and G.657 define allowable MFD values and variations. MFD mismatch can occur due to variations in fiber manufacturing. All fibers compliant to ITU-T G.652 and G.657 are fully intermatible and compatible.

OTDR and OLTS Testing

OTDR relies on backscattered light, which can introduce measurement artifacts. Backscatter variations in OTDR readings do not reflect actual transmission performance. OLTS provides a definitive measurement of link loss and should be the primary tool for loss verification, with OTDR reserved for mapping and troubleshooting.

By applying these insights, designers, installers, and operators can ensure reliable, high-performance fiber networks while avoiding misinterpretations in testing and measurement.

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.

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