Single Mode Fiber Bend Requirements in the Data Center

Prologue

This white paper is the first in a series aimed at clarifying the technical nuances of deploying single-mode optical fiber in modern, large data centers, including large enterprises, co-location facilities, hyperscale environments, and AI-specific data centers.

The paper examines the advantages of different optical fiber constructions, common cable designs and routing scenarios, and bend performance specifications within data centers.

Future white papers in this series will explore:

- The significance of micro-bending in deploying ultra-high fiber count cables
- The impact of Mode Field Diameter (MFD) variability on optical fiber network testing and operations

Contributors

Keith Sullivan
Director of Stategic Innovation, AFL

Alan Keizer
Senior Technology Advisor, AFL

Ben Atherton
Technical Author, AFL

Paige James
Design Manager, AFL

Fiber Optic Specifications

The Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T) provides specifications for optical fiber and optical fiber cables. While the ITU-T provides 'Recommendations,' these guidelines are widely accepted as industry standards for optical fibers and cables.

Throughout this white paper, we will focus on two specific ITU-T recommendations:

ITU-T G.652: Characteristics of a single-mode optical fiber and cable
ITU-T G.657: Characteristics of a bending-loss insensitive single-mode optical fiber and cable

The ITU-T G.652 recommendation specifies the mechanical, geometric, and transmission attributes of single-mode optical fiber and cable with a zero-dispersion wavelength around 1310nm. Initially optimized for transmission in the 1310nm wavelength region (Original Band or O-Band), this recommendation is also applicable for use in the 1550nm (Conventional Band or C-Band) and 1625nm (Long Band or L-Band) regions. G.652 includes four attribute tables for different transmission applications. Table 4, which contains G.652.D attributes, is recognized as the industry standard for high bit-rate applications in both telecom and data center networks.

The attribute table is divided into two sections: Fiber attributes and Cable attributes. The Fiber attributes encompass key geometric properties (such as Mode Field Diameter (MFD), Cladding Diameter and Core-Cladding concentricity), transmission characteristics (including Cut-off Wavelength and Chromatic Dispersion), and macrobend loss. The cable attributes recommend cabled attenuation and Polarization Mode Dispersion, but do not include any recommendations for bending performance of optical fiber cable.

The ITU-T G.657 recommendation details the enhanced macrobend performance of G.652.D fibers when used in optical access networks (fiber-to-the-home, or FTTH). There are two categories of recommendations: G.657.A and G.657.B. Category A pertains to access networks, often referred to as 'the last mile' of a fiber to the home network. Category B pertains to building networks, where fibers are routed inside buildings or homes, potentially pinned to walls, and routed around the home. Category A fibers must fully comply with G.652.D fibers, while Category B fibers are not necessarily compliant with G.652.D fibers.

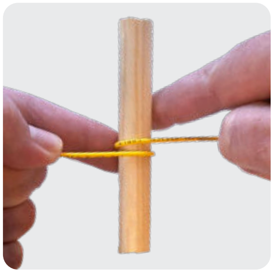
Importantly, this recommendation specifies the maximum bare fiber macrobending loss at 1550nm and 1625nm for different bend radii but does not address loss at 1310nm.

Category	ITU-T G.657.A1		ITU-T G.657.A2			ITU-T G.657.B2			ITU-T G.657.B3			Unit
Radius	15	10	15	10	7.5	15	10	7.5	10	7.5	5	mm
Number of Turns	10	1	10	1	1	10	1	1	1	1	1	
Max @ 1550nm	0.25	0.75	0.03	0.1	0.5	0.03	0.1	0.5	0.03	0.08	0.15	dB
Max @ 1625nm	1	1.5	0.1	0.2	1.0	0.1	0.2	1.0	0.1	0.25	0.45	dB

Fiber Bending vs Cable Bending

Fiber bending refers to the bending of bare optical fiber. Some optical fibers are engineered with specially optimized core and cladding structures to minimize the effects of bending by maintaining light within the fiber core. These specialized structures are necessary to meet the bending performance standards outlined in the G.657.A2 and B3 recommendations (at 1550nm and 1625nm) for FTTH applications. However, such structures are not required for G.652.D or G.657.A1 performance or for transmission at 1310nm.

Fiber wrap on A2 Mandrel



Patchcord wrap on A2 Mandrel

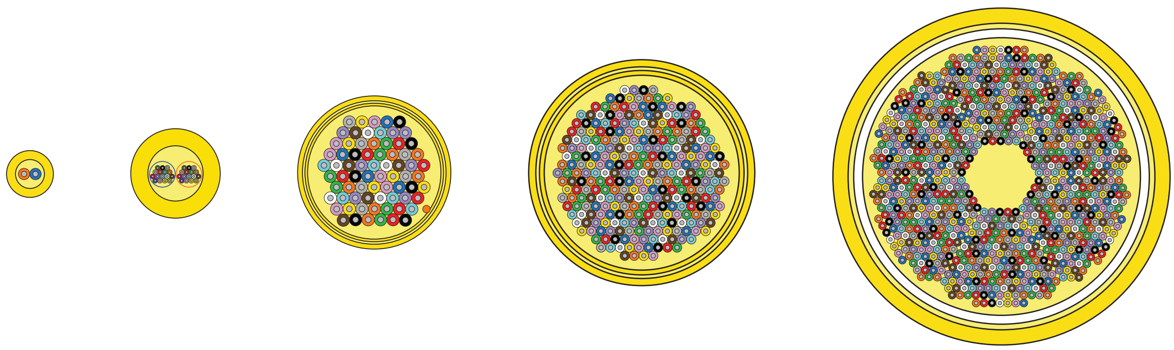
Cable wrap on A2 Mandrel (with high force)

Cable wrap on A2 Mandrel (with excessive force – cable kinking at the bottom)

Cable bending performance refers to the bending of an optical fiber cable, which includes the fiber, buffer, strength members, and outer jacket. The construction of the cable contributes significantly to lifetime performance and typically determines the bend radius – often specified as ten times the cable diameter. For cables with fiber counts greater than twelve, bending to the radii specified in the G.657 recommendation would be physically impossible without causing permanent damage.

The G.657.B recommendation was introduced for applications where fiber is run inside buildings or homes. In these scenarios, miniaturized optical cables with one or two fibers are routed through the building's interior, often stapled or tacked to walls or skirting boards, achieving the small radii specified in the G.657 recommendation.

In contrast, data center cables generally have higher fiber counts, resulting in larger diameters and stiffer constructions that cannot bend to the radii specified by G.657. These cables are typically routed in basket trays with large bend radii and relatively straightforward routing.

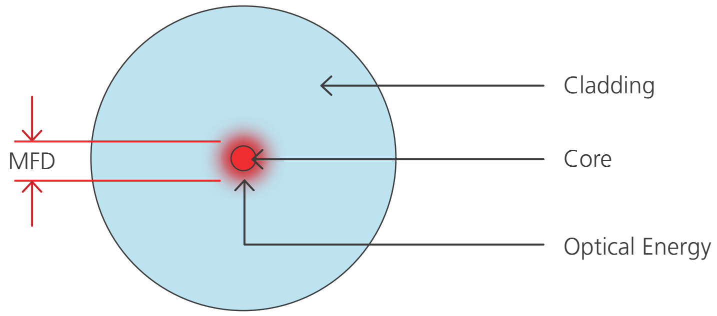


2mm	3.8mm	6.4mm	9.5mm	14.3mm
Round Duplex	Round 32f	Round 72f	Round 288f	Round 864f

Cable images are not shown to scale but accurately represent the relative size differences between cables.

Mode Field Diameter (MFD)

MFD measures the diameter of the light beam within the fiber. The core diameter refers to the physical dimension of the core glass. MFD is typically larger than the core diameter because some light spills into the cladding. MFD increases with wavelength; for instance, a 9µm core diameter might have an MFD of 9.2µm at 1310nm and 10.4µm at 1550nm.



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

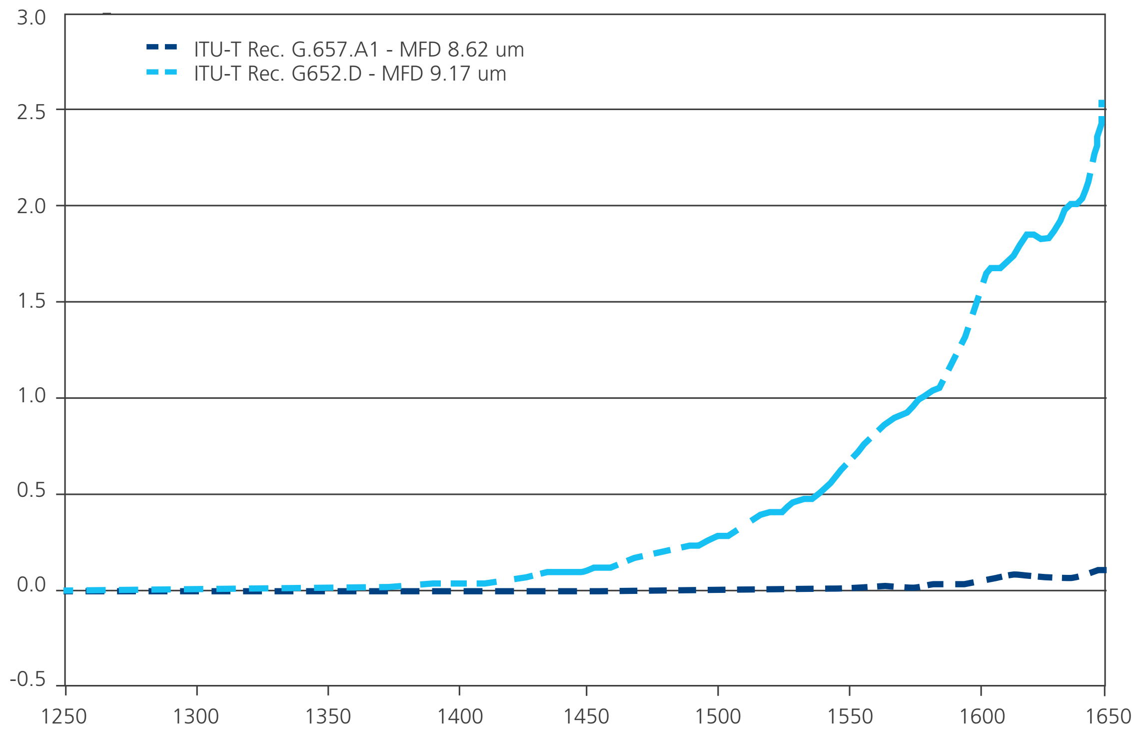
MFD is wavelength-dependent and is specified in the G.652.D recommendation at 1310nm. In this document, any reference to a fiber's MFD pertains to the MFD at 1310nm unless otherwise stated.

Comparing different MFD fibers reveals significant differences in bend performance, attenuation, and optimal use cases. 8.6µm MFD fibers offer enhanced bend performance suited to short or medium distances at 1310nm wavelengths, ideal for high-density data center environments. Conversely, 9.2µm MFD fibers are designed for lower loss performance over long-haul applications, typically seen in telecommunications networks. This lower loss at 1550nm is crucial for transmission distance in long-haul networks but comes with increased sensitivity to bending.

O-Band MFD	Pros	Cons
8.6µm MFD	- Enhanced bend performance - Lower chromatic dispersion (removes the need for Digital Signal Processing, especially at shorter lengths - <10km) - Optimum for 1310nm (short to medium distances)	- Higher attenuation – 0.35dB @1310nm - Higher power density
9.2µm MFD	- Lower attenuation – 0.18dB/km @1550nm - Lower Power density, giving a reduction in non-linear effects (beneficial for longer haul networks) - Optimised for long-haul, high-power applications	- Far more bend sensitive at telecom wavelengths

Wavelength and Mode Field Diameter in Relation to Bending

Bend sensitivity is significantly influenced by light wavelength and MFD, as illustrated:



1. Corning

The chart shows the loss induced on a fiber when wrapped one full turn around a 10mm radius mandrel. The light blue line represents the induced loss on a fiber with a 9.2µm MFD, and the dark blue line represents the loss on a fiber with an 8.6µm MFD. In the 1310nm window, both fibers exhibit close to zero bend-induced loss. Around 1440nm, the induced loss in the 9.2µm MFD fiber begins to increase, and at 1550nm, the G.657.A2 requirement of 0.1dB is exceeded. The 8.6µm MFD fiber maintains a negligible loss level up to 1600nm.

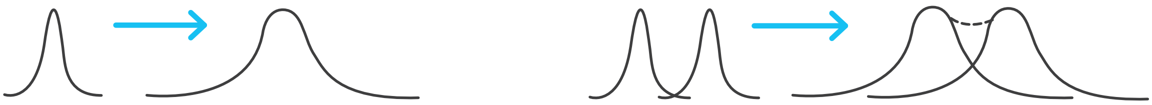
The results highlight the necessity to address bend sensitivity at the higher wavelengths used by telecom networks – particularly in fibers with larger MFDs, favored by these networks. More relevant to this white paper, at 1310nm (the preferred transmission wavelength for data center networks) both fibers exhibit near-total bend resilience. This eliminates the need for special bend-enhanced fibers and explains why the G.657 recommendation does not provide guidelines at 1310nm.

Common Transceivers and Applications

Optical fiber communication begins with a transmitter and ends with a receiver, often combined into a single device known as a transceiver. Key parameters of any transceiver include the power output of the transmitting laser, the sensitivity of the receiver (the lowest light level detectable), and the acceptable distortion of the laser signal over the fiber length. As laser pulses travel down the fiber, intensity decreases (attenuation) and the pulses widen (dispersion). Excessive pulse spreading can cause overlap, making individual pulses undetectable.

Chromatic dispersion is the most critical form of dispersion. This phenomenon occurs when different wavelengths of light travel at varying speeds through an optical fiber. For example, a 1310nm laser with a spectral width of 3-4nm (for example, from 1309nm to 1313nm) experiences chromatic dispersion due to these wavelength variations, causing light pulses to spread over time and distance, degrading signal quality and complicating data transmission.

Dispersion



As light pulses travel through optical fibers, dispersion causes pulse spreading, limiting the maximum transmission distance and the achievable bit rate.

At 1310nm, chromatic dispersion is nearly zero, eliminating the need for complex error correction mechanisms at lower power levels. This simplification results in cost-effective transceiver designs, enhancing reliability and overall efficiency of data transmissions, making 1310nm the optimal wavelength for data center applications.

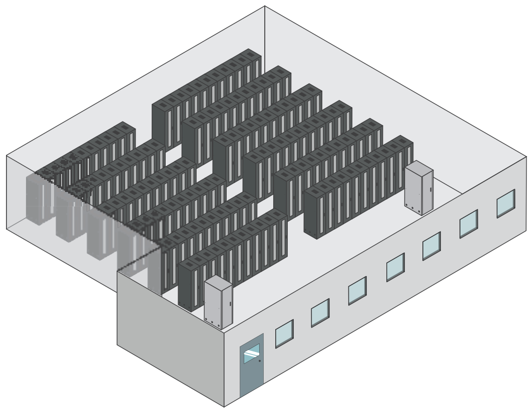
For long-haul telecom networks, the lower attenuation at 1550nm or even 1625nm is crucial for transceiver selection. Long-haul transceivers use more powerful lasers to cover greater distances, increasing power density in the fiber core and causing non-linear effects. Using a larger MFD reduces core power density, minimizing the need for expensive digital signal processing in the transceiver.

	1310nm	1550nm	1625nm
Chromatic Dispersion	Near Zero	13.3 - 18 ps/(nm.km)	17.2 - 22 ps/(nm.km)
Reach	Short to Medium (30m – 40km)	Long (Hundreds of KMs)	Long/Extended/Out of Band (Thousands of KMs)
Cost	Low	Medium	High
Bend Sensitivity	Near Zero	High	Very High

When discussing data center fiber networks, all areas must be considered:

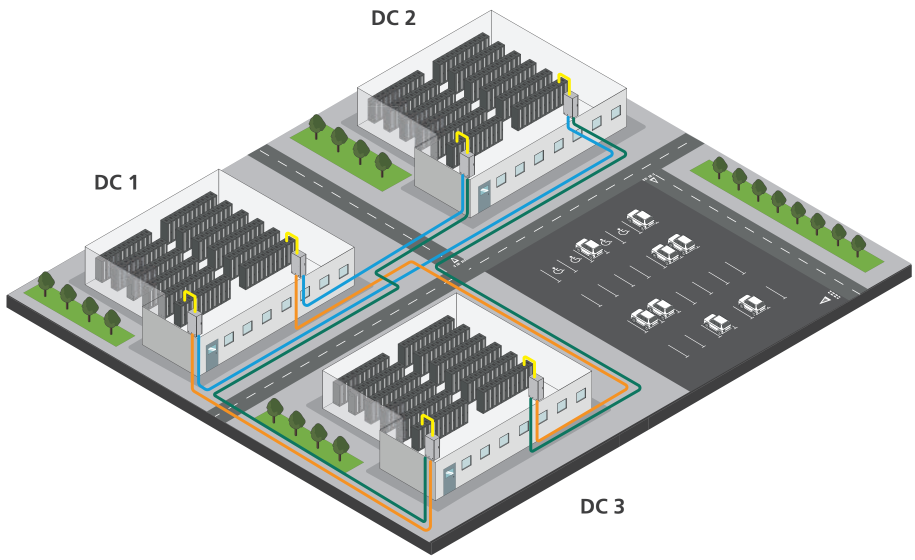
The White Space Network

This network, located inside the data hall, connects servers to switches and switches within the Spine & Leaf network. In high-end traditional cloud networks, the network operates at 400GB/sec, typically using DR4 transceivers (four lanes of 100GB/sec over four pairs of fibers) or FR4 transceivers (four wavelengths of 100GB/sec each over one pair of fibers). In high-end AI back-end networks, transmission speeds increase to 800G, using either DR8 (eight pairs of fibers) 2xDR4 or 2xFR4. Both DR and FR transceivers operate in the O-Band at 1310nm, with DR transceivers reaching up to 500m and FR transceivers up to 2km.



The Data Center Interconnect (DCI) Campus Network

This network connects data centers on the same site or campus. Distances, including diverse routing, range from a few hundred meters to 2km, rarely exceeding 5km. For this application, FR4 transceivers offer the optimal reach versus cost balance for distances up to 2km, while LR4 transceivers are suitable for lengths up to 10km. Both FR4 and LR4 transceivers operate in the O-Band.



The DCI Metro Network

Like the Campus Network, this network connects data centers across a metropolitan area for redundancy reasons. Distances range from a few kilometers > up to 40km. LR4 transceivers are used for lengths up to 10km, and ER4 transceivers for lengths between 10km and 40km. Both LR4 and ER4 transceivers operate in the O-Band.

Data Center Backhaul Network

This network connects data centers in different regions, countries, or states. The network can be run on the data center operator's own fiber infrastructure or more commonly on leased fiber from a local carrier service provider. This network resembles a telecom long-haul network, spanning hundreds or even thousands of kilometers. Transceivers in this space are highly specialized, incorporating extensive digital signal processing and enhanced detection, typically Coherent optics – ZR4 / ZR4+ resulting in a significantly higher cost—typically five times that of a DR4 White Space transceiver.

	800GBASE-2FR4 OSFP	800GBASE-DR8 2XMPO OSFP	800GBASE-2LR4 OSFP	400GBASE-ZR+ QSFP-DD
Product Image				
Form Factor	OSFP	OSFP	OSFP	QSFP-DD
Connector interface	2X LCD	2X MPO	2X LCD	LCD
Distance	2km	500m	10km	120km
Wavelength	1271nm, 1291nm, 1311nm, 1331nm	1310nm	1271nm, 1291nm, 1311nm, 1331nm	1550nm
Tx Power	-3.2 – 4.4dBm	-2.9 – 4dBm	-2.7 – 5.1dBm	-10 – -6dBm
Rx Sensitivity	-7.2dBm	-5.9 – 4dBm	-9dBm	-12dBm
Power Budget	4dB	3dB	6.3dB	6dB
Laser Type	EML	EML	EML	EML/DFB
Power Consumption	<16.5W	<16.5W	<16.8W	<21W
Average RRP	$1,600	$1,250	$2,200	$5,400

Over the years, transceivers for short to medium reach applications (up to 10km) have evolved in the O-Band due to the near-zero chromatic dispersion and the resulting simplicity of the transceiver design, which yields a significantly lower cost transceiver.

In a data center's white space, transceivers accumulate rapidly when building networks with end devices, top-of-rack switches, leaf switches, and spine switches. For instance, a 16k AI cluster (16,384 GPU accelerators) could require over 57,000 transceivers. Therefore, any cost increase per transceiver scales up quickly.

Conservatively, a coherent transceiver in the C-Band (400GBASE-ZR+) is $2,000-$3,000 more expensive per unit, which would result in an incremental $114 million at the low end if used in the white space. For a 64k cluster, the transceiver count increases to just under 230,000 units, resulting in an incremental cost of $458 million.

In the Mid-term, Will We Likely See a Move Away from 1310nm Transceivers in Data Centers?

The industry is unlikely to shift to 1550nm transceivers in data centers over the next five years for several compelling reasons:

Cost and Complexity

1550nm transceivers are significantly more expensive than 1310nm solutions. Additionally, the advanced technologies required for 1550nm may consume more power, increasing operational costs and impacting energy efficiency goals.

Chromatic Dispersion Challenges

At 1550nm, standard single-mode fiber (SMF) solutions exhibit higher chromatic dispersion, impairing signal quality over shorter data center distances. The zero dispersion at 1310nm makes this wavelength more suitable for data centers.

Compatibility and Standardization

Installing 1550nm optics would likely necessitate changes to existing infrastructure, potentially leading to compatibility issues. Furthermore, the industry currently lacks unified standards for 1550nm short-reach applications, making widespread adoption unlikely.

Standards activities

The IEEE 802.3dj Ethernet working group is focused on developing next-generation speeds of 800G and 1.6TB, with all public activities and documentation centered on the O-Band. Similarly, the Ethernet Alliance and High-Speed Ethernet Multi-Source Agreements (MSAs) are exclusively working on O-Band solutions for these advanced speeds.

At the time of writing, there are no ongoing activities related to short to medium reach transceivers in the C-Band.

Sufficiency of 1310nm for Short-reach Applications

1310nm optics provide sufficient performance and bandwidth for the short distances inside data centers. The cost-effectiveness, transmission performance, and inherent superior bend performance of 1310nm solutions are ideal for high-density, short-reach applications.

Due to minimal chromatic dispersion, cost-effectiveness, compatibility with existing infrastructure, and inherent bend performance, the 1310nm wavelength remains the optimal choice for data center transceivers. The challenges associated with 1550nm optics hinder widespread adoption.

Fiber Testing at 1310nm and 1550nm

G.657 recommendations do not address macrobend performance of optical fiber in the O-Band (1310nm) because G.652.D fibers exhibit excellent bend performance at this lower wavelength. Consequently, no specification or recommendation for bend performance at 1310nm is necessary.

However, when discussing bend performance generically as A1, A2, and B3, regardless of wavelength, the following equivalent definitions can be used:

A1 Equivalent:
One turn around a **10mm radius** mandrel with a maximum attenuation increase of 0.75dB

A2 Equivalent:
One turn around a **7.5mm radius** mandrel with a maximum attenuation increase of 0.5dB

A3 Equivalent:
One turn around a **5mm radius** mandrel with a maximum attenuation increase of 0.15dB

Using these equivalent performance metrics, a simple test was conducted to measure attenuation increase for the three performance grades at 1310nm and 1550nm. The test involved AFL/FJK SR15E fiber (standard G.652.D fiber with an 8.6µm MFD) and two other fibers with a 9.2µm MFD, using a duplex LC patchcord for each variant.

G.657 recommendation specify the following values:

Category	ITU-T G.657.A1		ITU-T G.657.A2			ITU-T G.657.B2			ITU-T G.657.B3			Unit
Radius	15	10	15	10	7.5	15	10	7.5	10	7.5	5	mm
Number of Turns	10	1	10	1	1	10	1	1	1	1	1	-
Max @ 1550nm	0.25	0.75	0.03	0.1	0.5	0.03	0.1	0.5	0.03	0.08	0.15	dB
Max @ 1625nm	1	1.5	0.1	0.2	1.0	0.1	0.2	1.0	0.1	0.25	0.45	dB

Our simple test yielded the following results:

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

SR15E (8.6µm MFD) A1
Mandrel (Ø20mm)
1310nm – 0.01dB
1550nm – 0.03dB

SR15E (8.6µm MFD) A2
Mandrel (Ø15mm)
1310nm – 0.01dB
1550nm – 0.37dB

SR15E (8.6µm MFD) B3
Mandrel (Ø10mm)
1310nm – 0.12dB
1550nm – 3.14dB

The AFL/FJK SR15E fiber passes the A1, A2 and B3 equivalent performance at 1310nm.

Addressing Market Misconceptions

Marketplace misconceptions often stem from creating or amplifying unfounded claims (or claims supported by minimal or anecdotal evidence). Such claims may center on the performance and suitability of data center hardware components, distorting perceptions of a product's capabilities and benefits.

Types of bend performance misinformation include:

Over-specification

Claims that only A2 or B3 fibers are suitable for data center applications, while suggesting that other fibers like A1 are inadequate, can lead to costly over-specification and added build complexity. As mentioned, all data center transceivers operate in the O-Band at 1310nm, and at 1310nm, all G.652.D compliant fibers are inherently bend insensitive. According to the testing section included in this white paper, the Fujikura SR15E fiber, with an 8.6μm MFD, exceeds the A1, A2, and B3 equivalent bend performance at 1310nm.

Bend Performance (at Irrelevant Wavelengths)

Data center transmission occurs at 1310nm. Highlighting bend performance at irrelevant wavelengths (e.g., 1550nm, 1625nm) can mislead customers into believing higher bend performances at these wavelengths are necessary.

Complex Manufacturing Processes with Excessive Costs

Manufacturing fibers with optimized core and cladding structures to meet the requirements of G.657.A2 and B3 (at 1550nm and 1625nm) is more costly and time-consuming. For data center transmissions, these fibers are excessive and add no value.

Summary

The G.657.A1, A2, and B3 specifications from the ITU-T apply to bare fiber at wavelengths of 1550nm and 1625nm.

Inside data centers, all transmission occurs at 1310nm and will continue to do so for the foreseeable future.

At 1310nm, all G.652.D compliant fibers exhibit excellent bend performance.

The AFL/FJK SR15E fiber meets A1, A2, and B3 equivalent bend performance on jumpers at 1310nm.

Misinformation exists claiming that specialist bend-insensitive fibers are required for data center applications, leading to over-specification, inflated pricing, and blocking techniques.

The IEEE 802.3dj working group is focused on developing next-generation speeds of 800G and 1.6TB, with all public activity and documentation centered around the O-Band. Similarly, the Ethernet Alliance and High-Speed Ethernet MSAs are exclusively working on O-Band solutions for these next-generation speeds. Notably, there is no activity related to the C-Band underway.

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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