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Application Note

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Low Loss Connectors and Fiber Outside Diameter

JANUARY 2024
Rev. 01

Issued by:
Engineering Department

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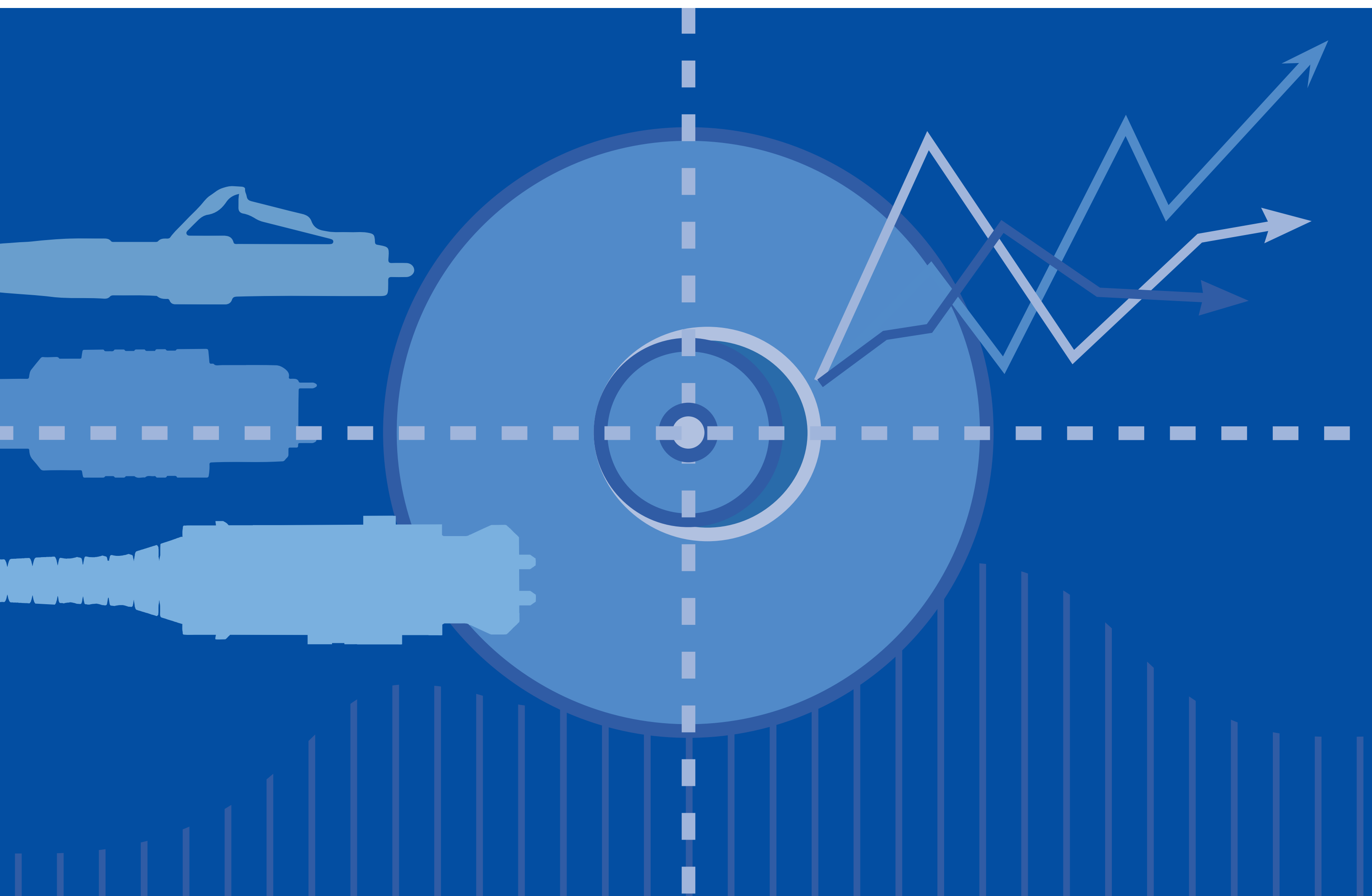

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Introduction

SENKO provides a wide range of connectors designed for diverse fiber optic applications. But what exactly sets a fiber optic connector apart in terms of its merits? The primary purpose of a fiber optic connector is to terminate the ends of fiber optic cables, ensuring they can be interconnected reliably with minimal optical loss. After termination and interconnection, two critical parameters come into play: Insertion Loss (IL) and Reflection or Return Loss (RL). A superior connector will exhibit minimal optical loss, thanks to precise alignment of the connected fiber cores and enhanced stability.

In essence, the demand for a fiber optic connector is driven by these qualities: reduced loss, cost-effectiveness, and ease of termination. Consequently, the market has seen the introduction of numerous fiber optic connectors, each adhering to various standards and serving specific applications. However, only a select few dominate the market, with even fewer standing out for their exceptional quality.

One crucial factor that determines a connector's quality is the zirconia ceramic ferrule. The degree of ferrule concentricity and the tightness of the ferrule's inner diameter (ID) are key factors that influence the extent of lateral misalignment during connection. Lateral misalignment, rather than longitudinal air gaps or angular misalignment, is a primary contributor to interconnect loss.

When estimating insertion loss (IL) resulting from lateral misalignment s, the following theoretical calculations were considered. The equation used:

$$IL\,(dB) = -10 \log e^{-U^2}$$

$$U = \frac{x}{\omega o}$$

x = core misalignment;

$$\omega o = a\left(0.65 + \frac{1.619}{V^{1.5}} + \frac{2.879}{V^{6}}\right)$$

ωo – single mode fiber (SM) spot size determined empirically with α as a fiber core radius and V as a normalized frequency – dimensional number used to describe the characteristics of SM fibers, depending on refractive indexes of fiber core/cladding.

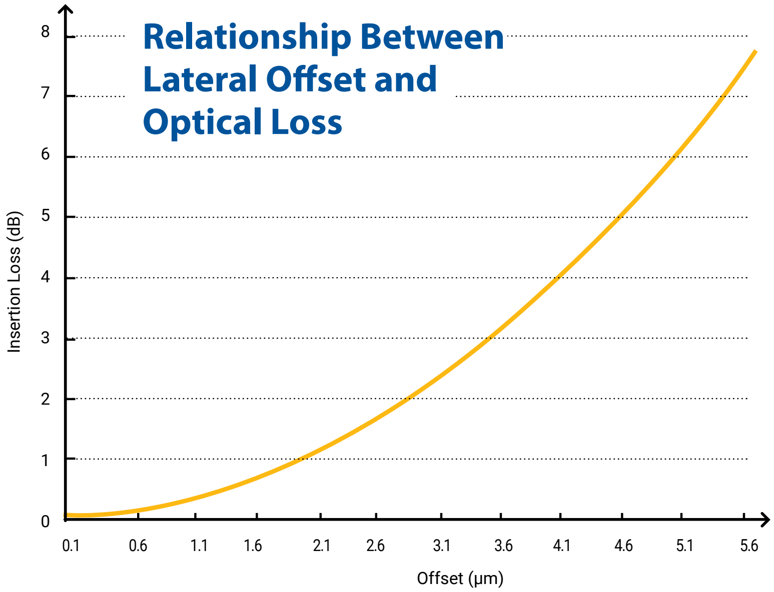


Figure 1 *Relationship between lateral offset and optical loss.*

It's reasonable to assume that a connector with tighter ferrule ID tolerances will yield superior optical performance. However, one must also consider the tolerances associated with the cylindrical silica glass outer diameter (OD) of the fibers. Ensuring there is no overlap in tolerances between the ferrules and the fibers is crucial to prevent misfit issues. Connector termination processes cannot afford production slowdowns due to trial-and-error attempts to fit tight ferrules onto equally tight fibers, nor can they risk scrapping connectors due to misfit problems arising from tolerance overlaps.

SENKO's range of connectors offers various ferrule grades, spanning from Low Loss to Premium to Standard. These options cater perfectly to different fiber types and applications, aligning with specific loss requirements.

Now, let's delve into what sets SENKO's connector offerings apart from the competition.

Discussion

There are two critical parameters in a fiber optic connection: Optical Insertion Loss (IL) and Optical Return Loss (RL). IL measures the power loss during signal transmission, while RL measures the amount of reflected light. Both parameters are crucial for assessing the performance and quality of optical components and connections in fiber optic systems. Lower IL and RL values are required for efficient and reliable optical communication. They are used to characterize the quality of optical connections and the efficiency of signal transmission in fiber optic networks. Here are their definitions:

Optical Insertion Loss

Optical Insertion Loss, often simply called ***Insertion Loss (IL)***, is a measure of the amount of optical power that is lost when light is transmitted through an interconnect. It quantifies the reduction in signal strength that occurs as light travels through a connection point. Expressed in decibels (dB), IL is typically displayed in a positive notation. Lower insertion loss values indicate better signal transmission efficiency.

Optical Return Loss

Optical Return Loss, also known as ***Return Loss*** or ***Optical Reflectance***, measures the amount of light that is reflected back towards the source when it encounters a discontinuity or reflection point in the optical interconnect. In other words, it quantifies the amount of optical power that does not get transmitted through the system and is instead reflected. Expressed in decibels (dB).

To minimize both IL and RL in fiber optic systems, precise alignment of fiber cores without any air gap between them is crucial. This process begins with the use of high-quality ceramic ferrules that exhibit near-zero eccentricity and concentricity values and have tightly controlled fiber hole inner diameters (IDs). Additionally, RL is managed during the manufacturing process by automated polishing of ferrules to meet specified geometrical standards and ensuring a defect-free optical endface.

In the past, ferrule and fiber tolerances were less stringent compared to today's requirements, driven by the need to reduce optical losses. To achieve this, a technique known as "Tuning" was commonly employed. Tuning involved orienting the fiber core in a specific position, typically aligning it with the key direction of the connector. By aligning the fiber core offset (also referred to as eccentricity and concentricity error) of each ferrule in the same direction, the total lateral offset between the joining fiber cores could be reduced compared to random orientation, thereby minimizing optical loss.

However, it's important to note that this tuning technique is effective only when a tuned connector is mated with another tuned connector, ensuring that the fiber cores are rotated and placed in the same orientation. Mating a tuned connector with a standard one negates the advantages of low loss achieved through tuning, which is a common occurrence in the field. Therefore, tuning is not a viable or practical option.

So, what are the critical factors that connector manufacturers need to consider in achieving low insertion loss measurements? Assuming that connectors are clean, free from foreign particles and defects, and adhere to GR-326 requirements in terms of geometry, the most critical aspects are:

Critical factors for Low Insertion Loss

1.)

Ferrule Hole Diameter

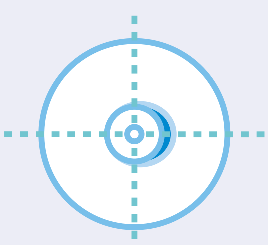
The ferrule is the most important component in a fiber optic connector that ultimately bears responsibility for optical loss values. For a minimum Insertion Loss, you should use the tightest-tolerance ferrule hole diameter available. For example, if the typical values for a single-mode fiber glass Outer Diameter (OD) are 124.5μm to 124.9μm the desirable ferrule Inner Diameter (ID) should be 125μm to 125.5μm.

2.)

Ferrule Hole Eccentricity

Ferrule hole eccentricity measures the deviation or displacement of the center of one shape from the center of another shape. In the context of a ferrule, eccentricity refers to the linear distance between the true center of the ferrule hole and its ideal position. It's crucial for the hole in the ferrule to be perfectly centered; otherwise, proper fiber alignment cannot be achieved.

3.)



Ferrule Hole Concentricity

Ferrule hole concentricity assesses the alignment of the centers of two or more shapes. In the context of a ferrule, it refers to the roundness and positioning of the bore hole within the ferrule. If the bore hole deviates from a perfectly round shape, you introduce another variable known as ferrule hole concentricity, which measures the alignment of the bore hole's inside diameter (ID) with its outside diameter (OD). An oval-shaped bore hole, rather than a perfectly round one, will not secure an optical fiber in perfect alignment.

Ferrule manufacturers typically specify ferrule hole concentricity to simplify terminology, assuming all three aspects mentioned above are in context. In this case, for SENKO Low Loss ferrules concentricity value is considered to be ≤0.3 µm, SENKO Premium Loss concentricity value is considered to be ≤0.6 µm, and the Standard Loss concentricity value is considered to be ≤1.0 µm.

Therefore, it's important to use ferrules considering the above tolerances for optimum performance.

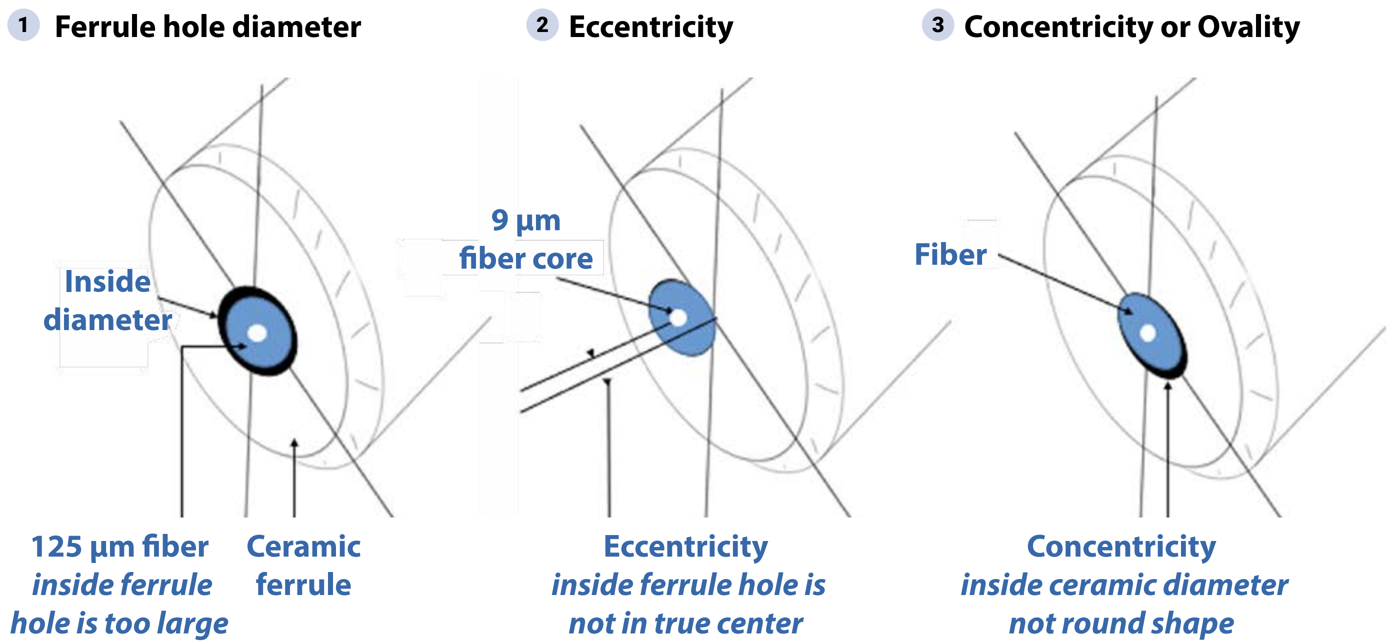


Figure 2 *Examples of defects in ceramic ferrules that result in lateral misalignments. Note, the images are exaggerated for demonstrative purposes*

After we have established the differences in concentricity values among the ferrule manufacturers, we will explore how these variations may impact the manufacturing process on the production floor, which is responsible for terminating connectors with optical fibers.

The outer diameter (OD) tolerances for optical single-mode fibers can vary depending on the specific fiber specifications, manufacturer, and industry standards. However, there are common industry standards that provide guidance on these tolerances. The International Telecommunication Union (ITU) has established standards for optical fibers, including single-mode fibers. According to ITU-T G.652, which defines the characteristics of standard single-mode optical fibers (also known as G.652 fibers), the typical outer diameter (OD) tolerance for these fibers is within the range of ± 0.5µm. It's important to note that different types of single-mode fibers, such as those optimized for specific applications or wavelength ranges (e.g., G.657 fibers for bend-insensitive applications or G.655 fibers for long-haul applications), may have slightly different OD tolerances. Therefore, it's advisable to understand the specific fiber specification provided by the manufacturer or perform your own study for precise information on OD tolerances for the particular type of single-mode fiber you are using or considering.

However, if you look at the specification sheets for Corning® SMF-28e+® LL optical fiber the Glass Geometry will look like as follows:

Dimension Specifications

Glass Geometry	
Fiber Curl	≥ 4.0 m radius of curvature
Cladding Diameter	125 ± 0.7 µm
Core-Clad Concentricity	≤ 0.5 µm
Cladding Non-Circularity	≤ 0.7 %

Coating Geometry	
Coating Diameter	242 ± 5 µm
Coating-Cladding Concentricity	< 12 µm

Figure 3 *Fiber glass specifications for Corning® SMF-28e+® LL optical fiber as published.*

In practice, leading fiber manufacturers often maintain significantly tighter tolerances for the outer diameter (OD) than ±0.5 µm. The actual statistical data from a fiber manufacturer is typically proprietary and not publicly shared. However, SENKO gained extensive experience in estimating actual fiber sizes from various suppliers. Typically, the ODs of leading fibers range from 124.7 µm to 125.3 µm, with a normal Gaussian distribution centered around the 124.9 µm value.

In the following example, we will demonstrate a straightforward method to estimate the implications of using super-tight ferrules with an assumed inner diameter (ID) range of 125.0 to 125.7 µm. To calculate the percentage of ferrule fallout due to tolerance overlap in the above scenario, we will assume that the ferrule sizes follow a Gaussian probability distribution (normal distribution). Using statistical calculation for a number N (mean, standard deviation) we have the following:

Problem: *Calculate the Percentage of Ferrule Fallout*

Ferrule ID (A) ~ N (125.35, 0.117)
Fiber OD (B) ~ N (125, 0.1)
The probability that the fiber is lager than the hole, **P(B > A) = P(B - A)**
The probabilistic variable **C = B - A** also follows a normal distribution:
C ~ N (125 - 125.35, 0.1 + 0.117) = N (-0.35, 0.217)

Our task is to find **P(C > 0)** - the probability of fiber being oversized.

In order to do this, we need to calculate the **Z-factor** and consult standard normal distribution tables N(0,1) or a calculator that is available on-line. **Z = -0.35 / 0.217 = -1.613**

We look up the table or use an on-line calculator (in the on-line calculator example you can simply set Mean=-0.35, SD=0.217 and compare it to zero).

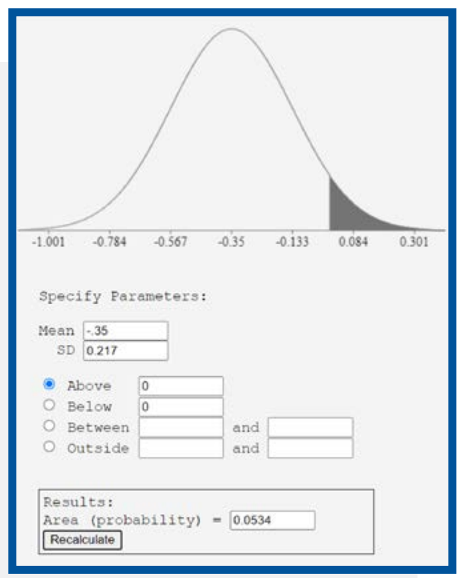


Figure 4 *Calculator for standard normal distribution.*

Answer: 5.3%

or 5-6 ferrules out of 100 could not go over the fiber

SENKO is aware of tolerance overlaps, drawing from its extensive experience with fibers from leading manufacturers. To mitigate misfit scenarios, SENKO shifts its ferrule ID distribution to the right, thus adjusting the normal curve accordingly. This approach minimizes the likelihood of overlap and misfit between the ferrules and the fiber distribution, all while ensuring the tightest and most manufacturable fit of the fiber into the ferrules. This, in turn, results in perfect core alignment and the lowest possible optical loss.

How optical loss is defined and what is the lowest possible loss? The losses are categorized by Grades that are defined in IEC 61753-1 document.

Insertion Loss criteria based on Random mating in the document IEC 61753-1 titled *Attenuation of Random Mated Connectors* which defines a certain minimum IL value of randomly mated connectors in a field setting and categorizes them into four different grades. It is important to note that the IEC 61753-1 defines connection performance grades for single-mode and multimode jumpers in a controlled environment. The standard gives four grades for IL from A (best) to D (worst) and RL, with grades from 1 (best) to 4 (worst). Grade "A" is not officially ratified by the IEC document, but most likely it will have similar optical performance reflected in Table 1 below.

Table 1 *IEC 61753-1 Proposed Attenuation Grade Jumpers*

Attenuation Grade	Attenuation Random Mated IEC 61300-3-34	
Grade A*	≤ 0.07 dB mean	≤ 0.15 dB max for >97% of samples
Grade B	≤ 0.12 dB mean	≤ 0.25 dB max for >97% of samples
Grade C	≤ 0.25 dB mean	≤ 0.50 dB max for >97% of samples
Grade D	≤ 0.50 dB mean	≤ 1.00 dB max for >97% of samples

Return Loss Grade	Return Loss Random Mated IEC 61300-3-6
Grade 1	≥ 60 dB (mated) and ≥ 55 dB (unmated)
Grade 2	≥ 45 dB
Grade 3	≥ 35 dB
Grade 4	≥ 26 dB

Specification	Each-to-each Values	Budget for 10 Connections
0.1 dB Connector	approx 0.2 dB *possibly higher if different manufacturers are combined or unadjusted connectors are used*	approx. 2 dB *unclear range of tolerance*
Grade C	≤ 0.25 dB mean, ≤ 0.50 dB max	≤ 2.5 dB
Grade B	≤ 0.12 dB mean, ≤ 0.25 dB max	≤ 1.2 dB
Grade A*	≤ 0.07 dB mean, ≤ 0.12 dB max	≤ 0.70 dB

* *Note, Grade A is not specified at time of writing, but assumed to be as shown*

SENKO offers ferrules that comply with any of the discussed grades from IEC 61753-1. The available ferrule offerings fall into three categories: Low Loss, Premium, and Standard. Today, SENKO customers have the option to order Low Loss ferrules with a maximum concentricity specification of 0.3µm, Premium ferrules with a maximum concentricity specification of 0.5µm, and Standard ferrules. The typical concentricity of Standard ferrules is also 0.5µm, with a slightly larger standard deviation compared to Premium ones.

SENKO's intermetability data using Low Loss ferrules demonstrate the ability to achieve Grade A, as proposed by IEC. However, during production, there may be occasional misfits due to the tight tolerances between the fiber OD and ferrule ID. Nevertheless, when working with leading fiber manufacturers, the misfit should not exceed 2-3%. Even in situations where the ferrule does not fit on a stripped fiber initially, it is likely to fit on the same fiber lot on a different area of the fiber, as the fiber OD varies slightly over the fiber's length. This trade-off results in premium optical loss, regarded as the best in the industry. If the stripped fiber does not fit a specific ferrule, it is common practice to put the ferrule off to the side and try another ferrule on the same stripped fiber. Afterwards, the ferrule that was put off to the side can be used for the next stripped fiber.

Low Loss connectors are used to manufacture reference cables, and in hyperscale data centers, where the link loss budget for 400GB+ transceivers can be as low as 1-2 dB, achieving minimal connection loss is critical. In emerging quantum computing, specifically Quantum Key Distribution (QKD) systems, there is a need for repeatable Low Loss connections to meet the requirements of Quantum Networking applications.

Premium ferrules are the most common SENKO offerings that meet the demands of today's most interconnect applications and are often recommended and used. With Premium ferrules, achieving IEC Grade B is possible without any production line slowdowns due to fallout or misfit. Furthermore, by employing SENKO Premium connectors and the ferrule tuning technique, it is possible to exceed Grade B Loss requirements.

Standard ferrules are often utilized in SENKO multimode connectors, or situation where Low Loss is not critical. The ferrules are still designed to have maximum tolerances on concentricity that align with single-mode requirements.

For a comprehensive summary of the anticipated optical losses under random mating conditions for all available ferrule types by SENKO, refer to the table provided below. This data originates from a study performed using SENKO single-mode LC Unibody connectors in a 10x10 random mating testing scenario.

Connector Type	IL Against Master	IL Random Mating	IL Random Tuned
Unibody Low Loss (dB)	≤0.05 mean / ≤0.15 max	≤0.125 mean / ≤0.25 max	≤0.02 mean / ≤0.14 max
Unibody Premium	≤0.085 mean / ≤0.20 max	≤0.15 mean / ≤0.305 max	≤0.04 mean / ≤0.17 max
Standard UPC	≤0.12 mean / ≤0.30 max	≤0.25 mean / ≤0.50 max	N/A

Table 2 *Random mated optical losses for SENKO Low Loss, Premium and Standard ferrules.*

Conclusion

SENKO provides a diverse range of connectors featuring **Low Loss**, **Premium,** and **Standard** ferrules, each tailored to meet various loss specifications. Selecting the most appropriate connector for a given application hinges on a thorough understanding of the optimal network optical loss budget and specific requirements.

It's important to recognize that tighter ferrule inner diameters and concentricity result in reduced lateral misalignment between mated cores, leading to the lowest optical loss, as defined by the IEC 61753-1 standard titled *Attenuation of Random Mated Connectors*. However, it's not always necessary to opt for **Low Loss** connectors, as this choice can potentially impact mass production efficiency when dealing with tightly fit fibers into ferrules, especially if the fibers are sourced from manufacturers with less stringent cladding OD tolerances.

In many applications, **Premium** connectors offer reliable and adequate performance. At SENKO, we encourage our customers to invest in quality connectors that not only adhere to the strictest tolerances for ferrule hole diameter, concentricity, and eccentricity but also align with their optical budget requirements.

For optimal results, it's important to consider that the fiber itself should have extremely low cladding OD tolerances, virtually zero core/cladding concentricity, and the production line must adhere to factory termination processes that comply with GR-326-CORE standards. By incorporating connectors that meet these rigorous tolerance criteria through world-class manufacturing processes, you set the stage for creating top-tier fiber optic cable assemblies that consistently deliver outstanding performance and long-term reliability.

SENKO's quality ferrule types:

Low Loss

Premium

Standard

GR 326 STANDARDS

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Biography

Andrei Vankov, is an Application Engineer at SENKO Advanced Components. He received his BS from Thomas Edison State College and his MSEE from Pennsylvania State University. He began his career in 1993 at Sumitomo Electric Lightwave Corp as a Fiber Optic Manufacturing Engineer where he worked on active and passive components using Kaizen methods in Yokohama, Japan. As a Senior Optical Design Engineer in Franklin, MA (founded as Advanced Interconnect) Andrei Vankov developed various passive optical components and packaging integration to meet Telcordia industry standards. He designed optical interconnects, including optical backplanes (MTP, HBMT, PHD, OGI), and a fiber optic SMPTE compatible Broadcast Connector for HD applications. In 2013-2020 Andrei worked at Nokia division Radio Frequency Systems (RFS) where he provided leadership for an LTE RAN launch project team. Andrei holds several US and European Patents in fiber optics interconnect technology.

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