

New, single-mode, multi-fiber, expanded beam, passive optical interconnect

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ABSTRACT

This paper describes the design and performance of next generation, single-mode, multi-fiber, debris insensitive, expanded beam, interconnect components. This low cost, dense optical interconnect technology combined with recent advances next generation, high bandwidth, SM, silicon photonic based Tx/Rx devices is enabling unprecedented bandwidth densities for extended distances at reduced costs.

A monolithic, multi-fiber ferrule with integrated collimating lenses was designed with the same overall footprint as a traditional MT-type, multi-fiber rectangular ferrule. The new optical ferrule was designed with precision micro holes for alignment to the lens array allowing for future incorporation of multiple rows of fibers into a single ferrule unit. The monolithic, lensed based ferrule design enables a low-cost, no-polish fiber termination methodology.

The ferrule tested was manufactured with an array of 16 fibers in the footprint associated with traditional, 12 fiber, physical contact MT ferrules via use of novel, molded in, end-face alignment features. Multiple optical models were built with ray tracing methodology to predict the insertion loss and return loss with varying refraction index, transmissivity and surface reflection properties of the ferrule.

Empirical optical performance results closely match the optical modeling predictions. Insertion losses of <1.5dB were measured along with return loss values ≤ -30 dB. Further analysis was done to characterize the robustness of the new interconnect with regard to debris insensitivity. Due to the nature of the expanded beam, free-space optical design, the impact of debris on the optical mating surface of the interconnect was significantly reduced when compared to traditional, physical contact single-mode interconnects

Keywords: Multi-fiber ferrule, MT ferrule, expanded beam, backplane connector, lensed connector, high density, embedded optic, Active Optical Cable

1. BACKGROUND: MID-PCB MOUNTED SINGLE-MODE OPTICAL DEVICES REQUIRE NEW CARD-EDGE PASSIVE INTERCONNECTS

Today, traditional single-mode optical communication links require an electrical to optical (EO) and optical to electrical (OE) conversion to occur within electronic equipment to carry electrical signals via copper Printed Circuit Board (PCB) traces into and out of the IC. Transceiver modules serving this function for long-reach, single-mode communication links are typically mounted at the edge of the communication equipment Printed Circuit Board (PCB). A common example of this type optical component is the Small Form Factor Pluggable LX format referred to as an (SFP) device which couples to duplex LC connectors. This configuration allows the passive optical fiber which will carry the signal from the equipment to be coupled directly to the EO/OE conversion module. Mounting the module at the edge of the equipment or PCB also allows for simple external exchanges for different protocol or length applications.

However, ever-increasing demand for bandwidth at lower costs is highlighting the limitations of this traditional communication link architecture:

- Cost structure
- Card edge/equipment space available for bandwidth I/O
- Thermal management challenges associated with dense EO/OE conversion aggregated at one edge of the PCB

- Signal integrity limitations and increased power requirements necessary to have longer electronic separation between computing Integrated Circuits and EO/OE conversion

Recent advances in optically enabled silicon IC devices are resulting in low cost single-mode Tx/Rx modules at costs comparable with multi-mode links which have much shorter reach limitations. The longest lengths in today's data centers are single-mode due to the link distances driven by size and layout of the data center. As costs for the single-mode optical links reduce relative to multi-mode, the need to maintain different equipment designs and link architectures for optimal cost/length optimization diminishes.

In addition, low cost single-mode Tx/Rx devices and ultimately photonic integrated ASICs will enable next generation backplanes for High Performance Computing (HPC), server, switching and routing equipment applications to migrate from electrical to optical and in single-mode rather than multi-mode form.

Mid-PCB mounted, low-cost, multi-mode, Tx/Rx EO/OE devices have led to the development of next-generation, low-cost, multi-mode passive optical interconnects. The following is a similar treatment of a similar approach for single-mode interconnects. Figure 1 highlights the I/O density advantages of embedded single-mode Tx/Rx devices with next generation, high density card edge connectors.

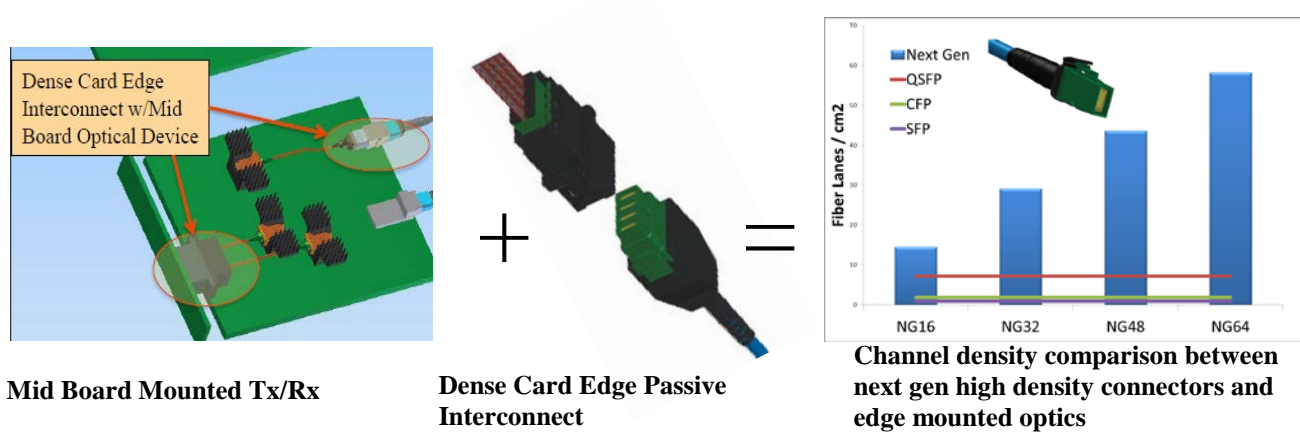


Figure 1: Channel Density at the card edge with embedded optics

2. TRADITIONAL MONOLITHIC FERRULES:

Multi-fiber ferrules commonly referred to as the "MT ferrule" or "rectangular ferrule" were originally developed by NTT Laboratories for use in subscriber network lines in an outside plant environment. The ferrules were initially molded out of a thermosetting epoxy material but migrated to a more environmentally stable thermoplastic material as precision molding technologies advanced. Due to the need for dimensional stability in the extreme operating environment, the ferrules are molded with a very high content of glass filler. In fact, the glass filler content can range from 60-80% by mass of the ferrule. Figure 2 highlights the glass filler appearance of a polished MT ferrule endface.

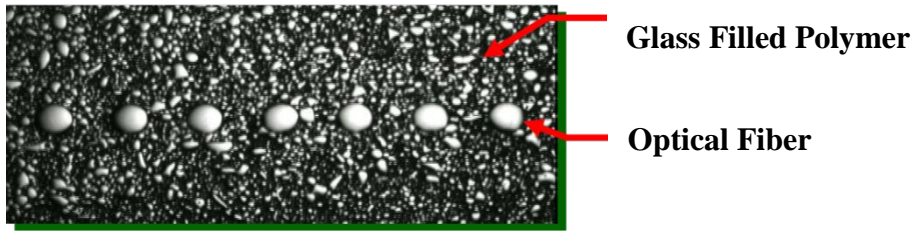


Figure 2: Traditional MT Ferrule endface appearance

Today's most common applications for multi-fiber connectors are structured cabling and external equipment interface for data centers and central offices which require very low insertion and return losses. Figure 3 shows insertion loss results for a random intermate of 12F fiber, low-loss, single-mode MT Elite® ferrule.

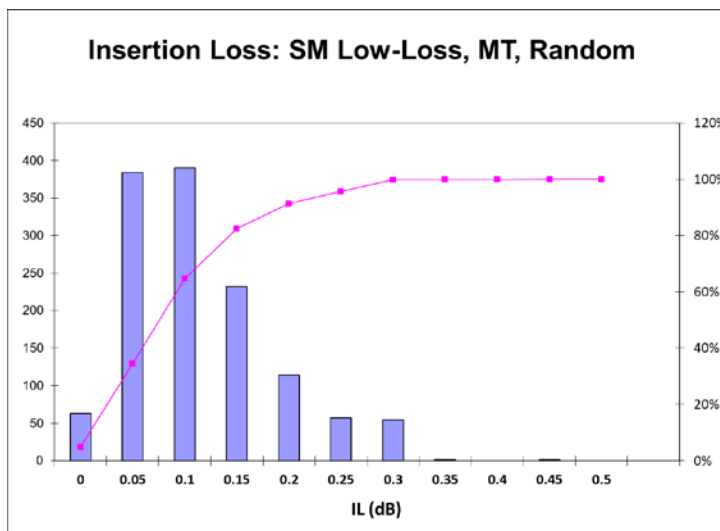


Figure 3: Empirical data: 12F, SM, Low-Loss MPO random intermate distribution

In order to obtain a low, stable, insertion loss, the glass fiber tip mated pairs must come into physical contact with each other. This physical contact requires very tightly controlled termination, polishing and metrology procedures which dominate the cost of traditional multi-fiber interconnects.

In addition to maintaining physical contact, each fiber tip in the ferrule must be kept pristine to ensure the signal is not attenuated through contamination blockage or loss of z-axis alignment (i.e., physical contact). Figure 4 illustrates the primary attributes impacting the performance of traditional MT based multi-fiber connectors: component precision, polished end face geometry, the ability to maintain physical contact, fiber tip quality, and cleanliness.

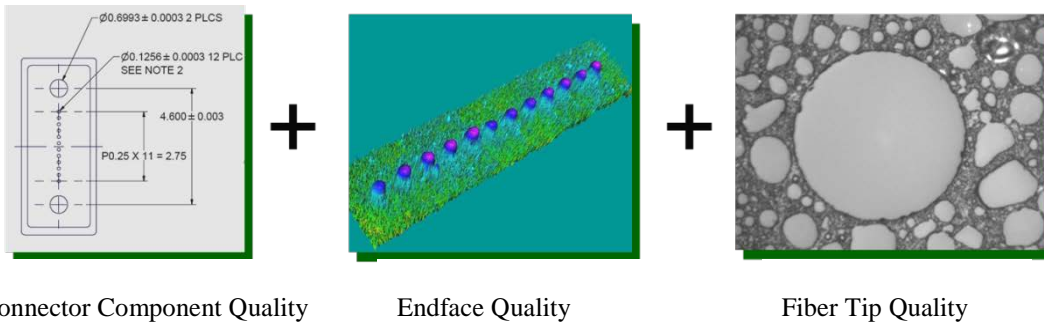


Figure 4: Factors impacting performance of traditional MT physical contact ferrules

State of the art polishing techniques for industry standard APC SM MT ferrule based connectors will only support up to 12 fibers in a single ferrule. For interconnect densities beyond 12 fibers, a flat polished ferrule end face is necessary which will support up to 24 fiber fibers within a single ferrule. However, per proposed IEC SC86B WG6 intermateability standards, a 23N spring load is necessary to achieve physical contact. a spring load of 23N is necessary to achieve and maintain physical contact. For fiber quantities beyond 24 achieving fiber tip physical contact is not feasible. As a result, the mated fiber tip interface of high fiber count ferrules (>24 fiber) becomes unstable which can result in optical interference and amplifying return loss values higher than a simple unmated connector will generate (i.e., unstable RL values can oscillate and peak at values below 10dB.)

While traditional, physical contact MT ferrules are suitable for demanding low-loss, high performance applications, they are not optimized for short reach, cost sensitive applications. In addition, because the bandwidth densities needed for emerging high-end optical backplanes require more than 24 channels, fiber physical contact is not a viable option. This has resulted in focused US Conec development activity on next generation optical backplane interconnects described in the following sections.

3. NON-PHYSICAL CONTACT CONNECTORS: EXPANDED BEAM

Expanded beam connectors are a subset of free-space optical interconnects. The “space” between the connectors must have a different index from the lens media for refraction to occur. Because of this fundamental rule, expanded beam connectors do not touch within the lens aperture. Use of expanded beam technology eliminates the need for fiber tip physical contact that ultimately reduces the overall cost of multi-fiber optical cable assembly manufacturing.

As shown in Figure 5, light emitted by the fiber diverges from the fiber tip through a homogenous optical optical polymer to the refractive boundary of a lens. Over this distance, the beam diverges based on the NA of the fiber and the index of the polymer. The resultant beam has a characteristic beam waist at the mating plane between the connectors. Beyond the mating plane, the beam begins to diverge in the far field region and is collected by the second optic where the beam focuses to the receiving fiber tip.

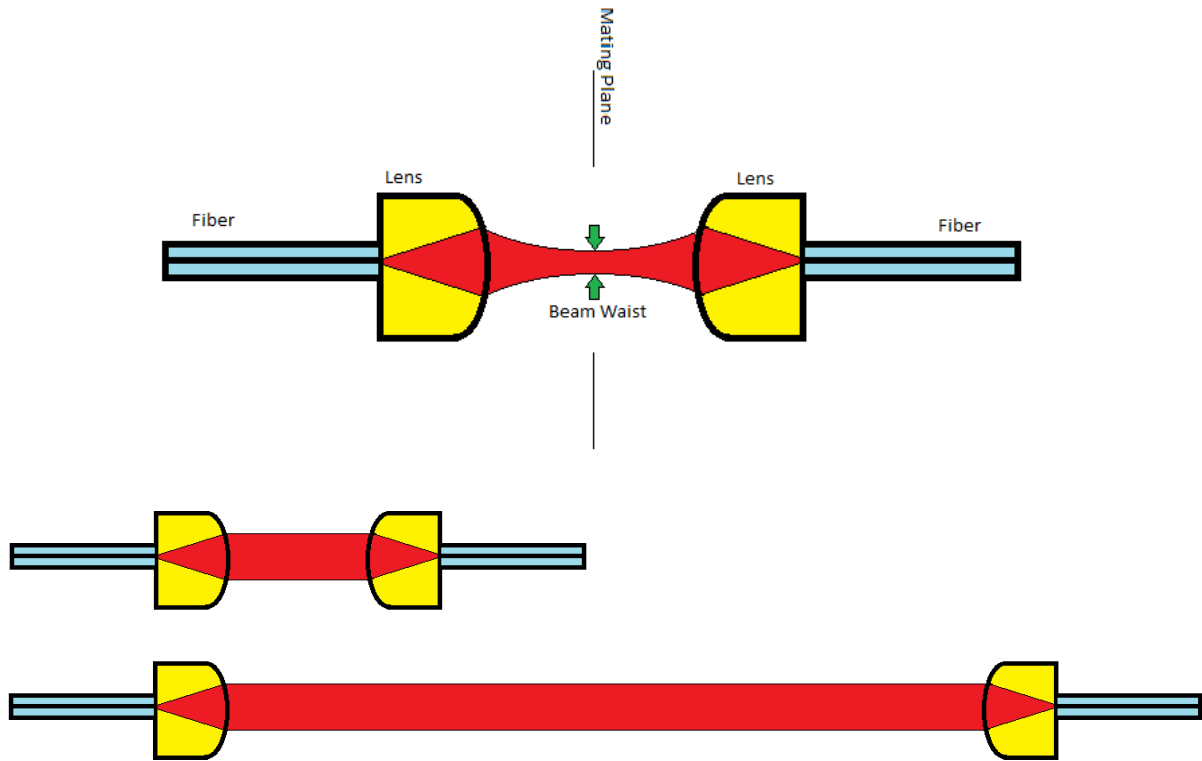


Figure 5: Insensitivity to Z-axis gap for the Ideally Collimated Lensed Connector

Some key advantages of an expanded beam interconnect are as follows:

1. The alignment precision required at the optical mating interface is significantly reduced. Consider the alignment necessary to effectively couple two, single-mode fiber cores with an effective Mode Field Diameter (MFD) of 9.2 microns at 1310nm. A three micron offset between the fiber cores results in an attenuation of 1.8dB. Now consider the same alignment offset at the mating interface for an expanded beam interconnect with a collimated spot size of approximately 90 microns with a Gaussian power distribution. The attenuation associated with the same three micron offset is 0.01dB. This reduced alignment precision at the mating interface introduces new options for alignment features associated with precision alignment.
2. The free-space nature of the interconnect eliminates the need for physical contact of polished fiber tips. For dense, multi-fiber interconnects, this is a significant cost savings due to the elimination of tightly controlled end face geometry, manufacturing processes and the minimization of ferrule mating forces
3. Expanding the signal to a larger area reduces the impact of debris by minimizing the impact of light occlusion and attenuation due to loss of physical contact.

4. INTEGRATION OF SINGLE-MODE COLLIMATING LENSES IN MONOLITHIC MULTI-FIBER FERRULES

We have previously demonstrated and released multi-mode, monolithic, molded, collimating multi-fiber ferrules for low-cost fiber to fiber coupling as well as fiber to Tx/Rx device coupling [1]. A similar ferrule structure and termination methodology was used for the single-mode interconnect and is described below. Key attributes of the ferrule structure are highlighted in Figure 6.

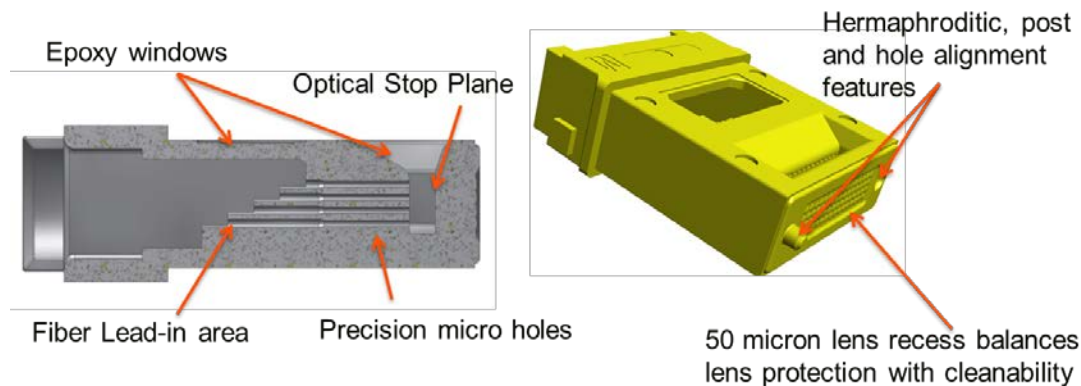


Figure 6: Single-Mode, monolithic, molded, expanded beam ferrule structure.

To reduce the cost associated with standard multi-fiber connectors, this new connector design completely eliminates the need for connector polishing and the costs associated with maintaining and measuring a pristine ferrule end face geometry. The following is a summary of the assembly and testing procedures:

Standard single-mode ribbon fiber is stripped and subsequently cleaved approximately 5mm beyond the end of the ribbon matrix. While traditional mechanical cleavers can be used, a laser cleaving process is recommended due to the resulting rounded fiber tips and clean end face. As compared to the fiber tips generated with a mechanical cleave, the rounded fiber tips reduce the amount of debris generated during fiber insertion. The cleaved fiber array is then inserted into the ferrule micro holes. Either a thermal cure or a light-curable index-matched epoxy is then inserted into both epoxy openings, and the fiber is pushed against the stop plane. Inserting the epoxy prior to pressing the fibers against the stop plane, ensures that the index-matching epoxy coats the fiber endfaces and eliminates air pockets between the fibers and the stop plane. The assembly is then cured using a light source or heat as applicable. The entire cleave, termination, and cure process can be completed in approximately one minute of labor time, greatly reducing the time involved in standard ferrule termination and polishing.

The expanded beam ferrule was designed with the same outer length, width, height and shoulder footprint as a traditional, physical contact MT ferrule. This aspect of the ferrule design allows for use with existing MT based connector solutions such as the MPO connector or other MT ferrule based connector solutions. Similarly, any future optical backplane interconnect architectures using this expanded beam ferrule technology will have the versatility to switch to traditional physical contact MT ferrules for applications requiring lower insertion losses and reduced back reflections.

The lensed ferrule was designed to be used without costly traditional MT guide pins. As described in Section 3, the precision required for alignment at the mating plane between the two ferrules is significantly reduced. As a result, molded in alignment features are sufficient to effectively align the collimated light interface. The ferrule end face is designed with one alignment post and one hole that couple and eliminate the need for a gendered connection as is the standard for multi-fiber interconnects.

Furthermore, the lensed ferrule platform was designed with a unique, high density lane interface footprint relative to traditional MT ferrules which supports up to 16 fibers in a single row.

As described in the Section 3 and Section 6 of this report, the impact of contamination on the lensed end face is less severe when compared to traditional, polished, physical contact fiber connectors. However, minimizing contamination and providing the ability to clean the connector endface when it is contaminated have been considered with the ferrule design. As shown in Figure 7, the lensed ferrule end face was designed to protect the optical transmission area by sealing off the lens array features on the mated ferrule pair. In addition, the lens array was only slightly recessed below the contact surface of the ferrule providing access to the lenses with an industry common contact based field or factory cleaning tool.

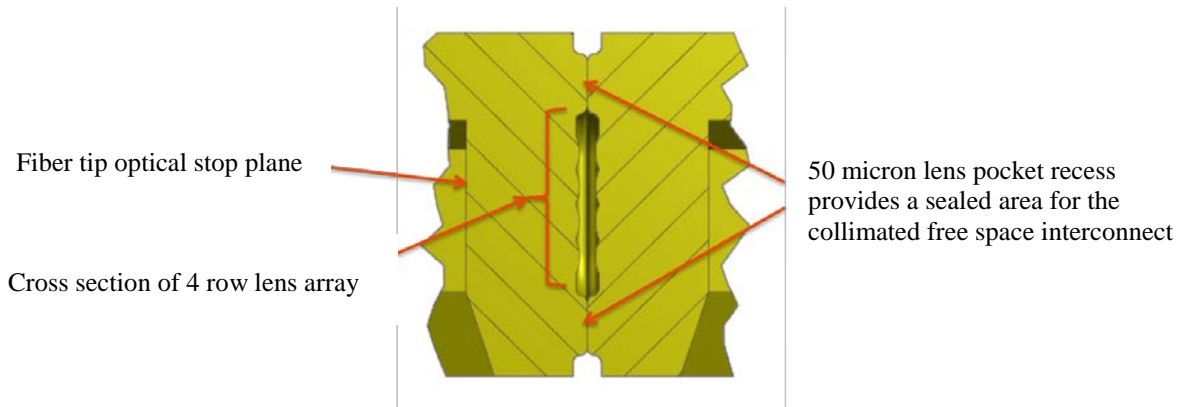


Figure 7: Cross-section of two mated, expanded beam ferrule endfaces

5. SM EXPANDED BEAM MT OPTICAL MODEL

An optical model was developed to simulate the insertion loss of the single-mode, lensed, multi-fiber ferrule. Zemax Software was used to develop the optical model. Tolerance values were assigned to the critical variables given in Table 1. The tolerance values assigned to the model were in line with alignment tolerances associated with typical, physical contact, single-mode interconnects.

A	Fiber Angle Relative to Lens	E	Lens Plane Angle Relative to Mating Plane
B	Lateral Fiber Offset Relative to Lens	F	Conic Conic of the Lens
C	Distance between Fiber and Lens	G	Radius of Curvature of the Lens
D	Lens Eccentricity Relative to Guide Hole and Guide Pin	H	Ferrule to Ferrule Lateral Alignment

Table 1 – Critical Variables Included in the Optical Model

Figure 8 illustrates the nominal ray trace model developed in Zemax. No anti-reflective coating was included in the model. A diagram showing the Fiber Angle Relative to Lens (A) and the Lateral Fiber Offset Relative to the Lens (B) is given in Figure 9. The model assumes that as the distance is increased between the fiber and the lens (C), the fiber is pulled away from the fiber stop plane and index-matched adhesive fills in the gap. The Lens Eccentricity Relative to Guide Hole and Guide Pin (D) represents the radial offset of the lens compared to the theoretical location of the lens relative to the guide hole and guide pin. The Lens Plane Angle Relative to Mating Plane (E) is illustrated in Figure 10. The Ferrule to Ferrule Lateral Alignment (H) is based on the guide hole and guide pin fit.

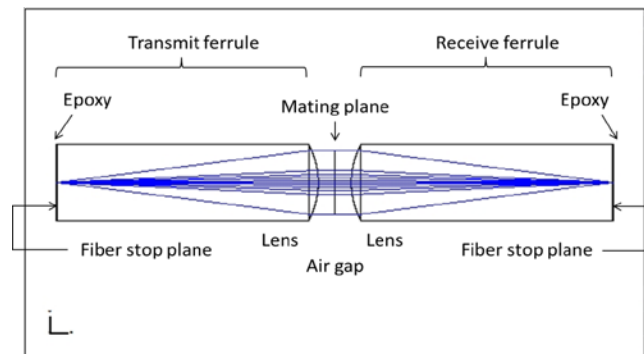


Figure 8 – Ray Trace Model in Zemax

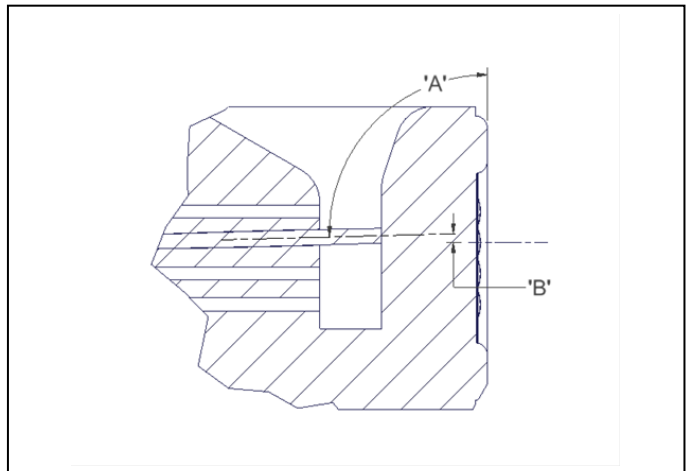


Figure 9 – Cross section of the ferrule with the Fiber Angle (A) and the Fiber Offset Relative to the Lens (B)

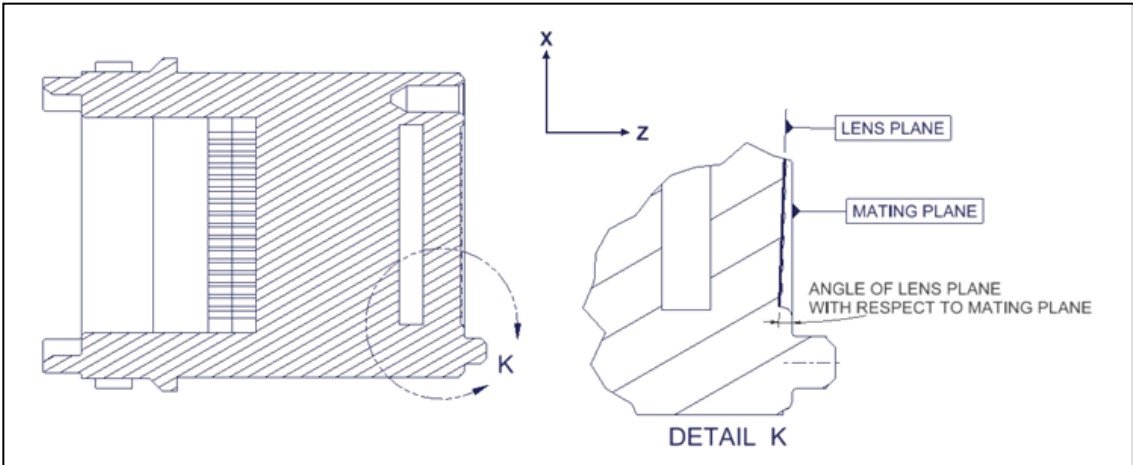


Figure 10 – Cross-section of the ferrule showing the Lens Plane Angle Relative to Mating Plane (E)

A monte carlo simulation was completed using a normal distribution tolerance range for each of the critical variables. The monte carlo solution was completed for two scenarios. First, a monte carlo simulation was completed for one ferrule that included all of the critical tolerance distributions mated against a perfect reference ferrule. A histogram of the results is shown in Figure 11. The average of the distribution is 0.74dB, the standard deviation is 0.19dB, and 98% of the channels are less than 1.26dB. Second, a monte carlo simulation was completed for two randomly mated ferrules. A histogram of the results is shown in Figure 12. In the case of two random ferrules, the average of the distribution is 0.99dB, the standard deviation is 0.38dB, and 98% of the channels are less than 2.1dB.

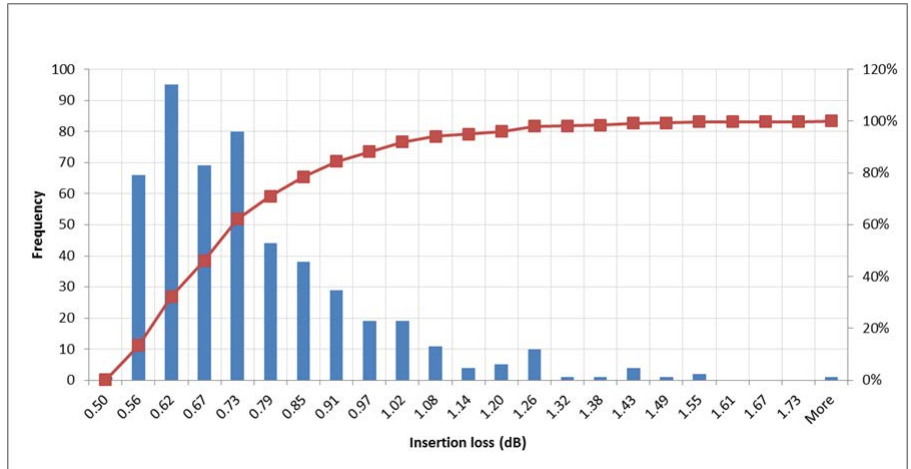


Figure 11: Insertion Loss Simulation – Ferrule Mated to Perfect Reference Jumper

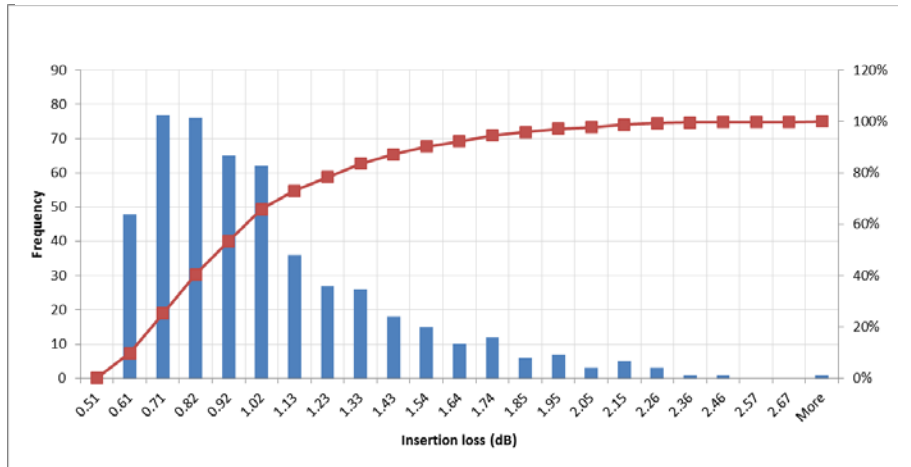


Figure 12: Insertion Loss Simulation – Two Randomly Mated Ferrules

The optical model simulated has inherent losses due to the Fresnel effects resulted from the refraction index changes between the glass fiber, ferrule and air. Subsequently, perfect alignment of the connectors in the model resulted in an insertion loss of approximately 0.49dB. The schematic in Figure 13 highlights the losses associated with those Fresnel effects. Changing the Fresnel effects can be accomplished by using materials with alternate refraction indexes or by applying an anti-reflection treatment on the surface of the lenses.

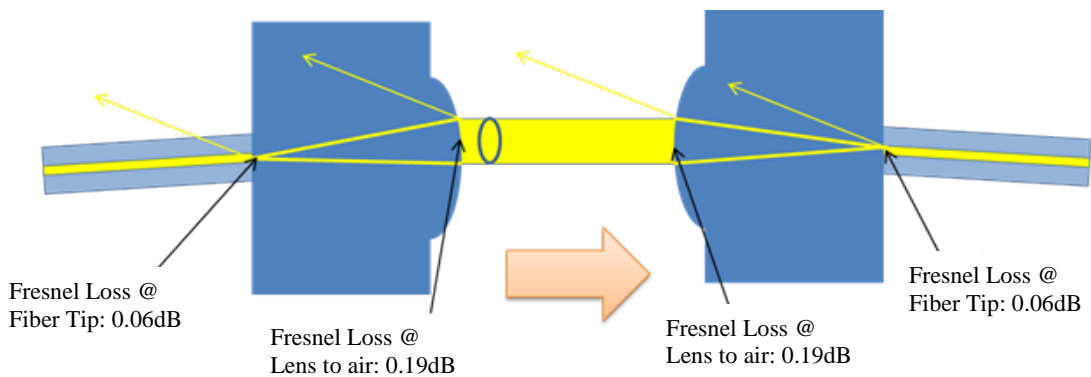


Figure 13: Losses due to reflections at changes in refraction index

6. EMPIRICAL RESULTS

A ferrule was manufactured in accordance with the description of Section 4. The ferrule produced and tested had a single row of 16 fibers for the empirical study.

The expanded beam ferrule was tested in a manner similar to standard fiber connector testing which uses conventional return loss and insertion loss test equipment. Unlike standard multi-fiber connectors however, this new lensed ferrule is designed to mate to another lens ferrule rather than to a standard ferrule with fiber to fiber contact. Therefore, unique testing procedures are necessary to utilize traditional fiber based test equipment. A schematic of the test setup is highlighted in Figure 14.

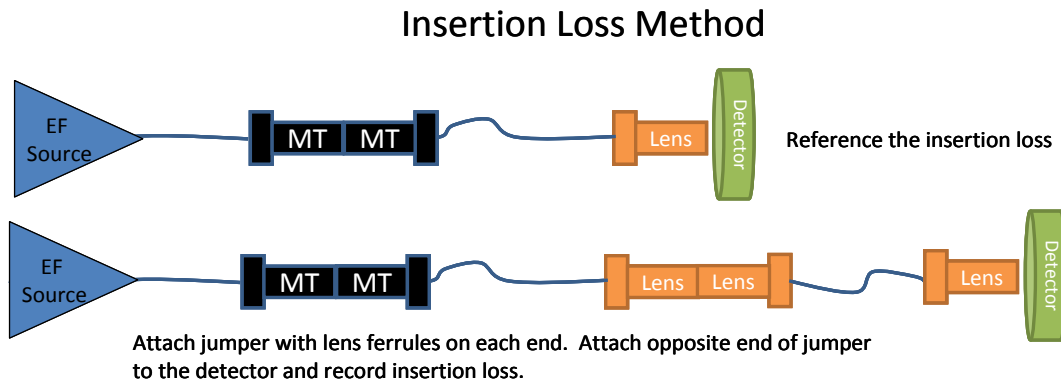


Figure 14 Insertion Loss Method

The insertion loss testing consisted of 10 randomly mated ferrule pairs. These ferrules were manufactured in accordance with the typical single-mode alignment tolerances associated with the optical model. The results are recorded in Figure 15.

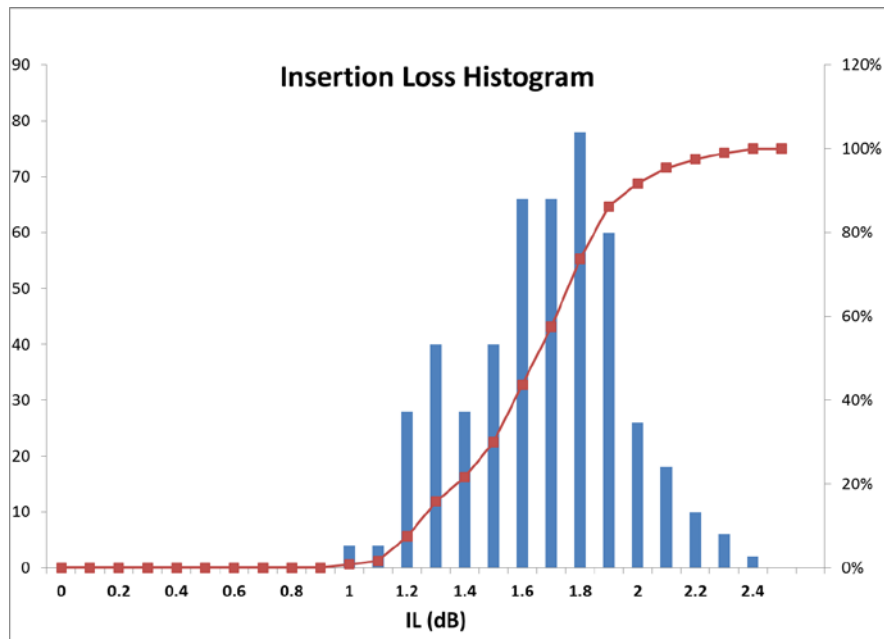


Figure 15: Insertion Loss results empirical results from random mate testing of the SM expanded beam ferrule

Unlike traditional, physical contact MT ferrules, the return loss at the lens to lens expanded beam interface is simply determined by the physical geometry of the lens. This gives the expanded beam ferrule a significant advantage over multi-row (>24 fibers??), high fiber count MT ferrules where reliable physical contact is unachievable. The value of the return loss measurement for the completed assembly is simply to verify that the termination was properly completed and that the fiber tips were correctly coupled to the stop plane within the ferrule. If the area between the fiber tips and stop plane contains voids or debris, poor return loss values of <20dB will be observed. The return loss results are reported in Figure 16.

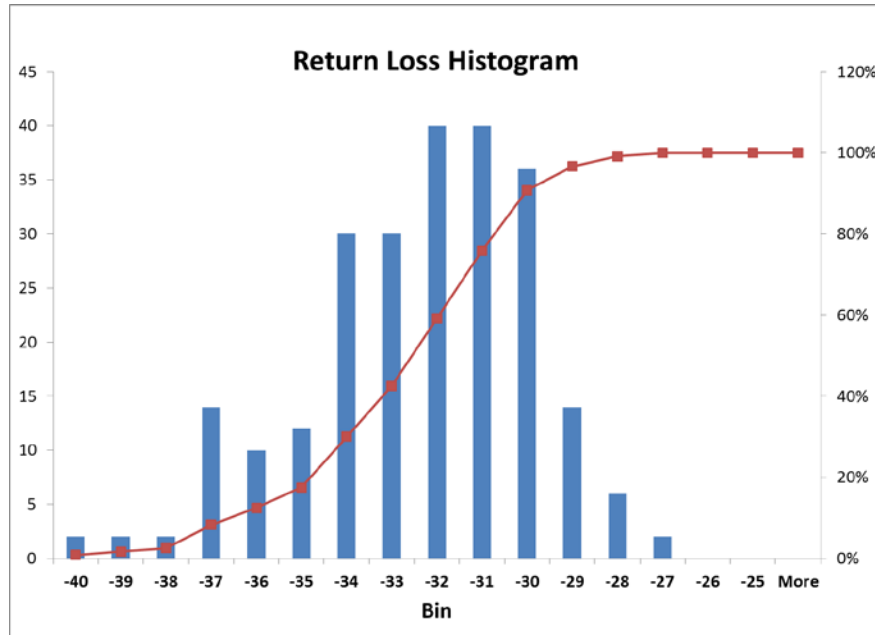


Figure 16: Return loss results from random intermate testing of the SM expanded beam ferrule

7. SM EXPANDED BEAM MT DEBRIS INSENSITIVITY

The single-mode, lensed, multi-fiber ferrule is significantly less sensitive to debris than traditional ferrules that rely on fiber physical contact. For the single-mode expanded beam ferrule, an index-matched adhesive encapsulates the fiber tip during fiber installation. The adhesive eliminates reflection losses by filling in small gaps that could occur between the fiber and the stop plane and the adhesive seals the fiber tip to prevent debris from contaminating the fiber tip in the field. By sealing the fiber tip in the factory during fiber installation, the lens surface is the only optical surface that must be kept clean. The beam size of the expanded beam is approximately 100 microns compared to a 9 micron fiber core in traditional ferrules.

The debris sensitivity of the two designs was compared using the simplified assumption that opaque, circular debris of varying diameters covers the center of the fiber tip or the center of lens. The calculations completed assumed a Gaussian power distribution. The insertion loss increase as a function of the debris diameter is shown in Figure 17.

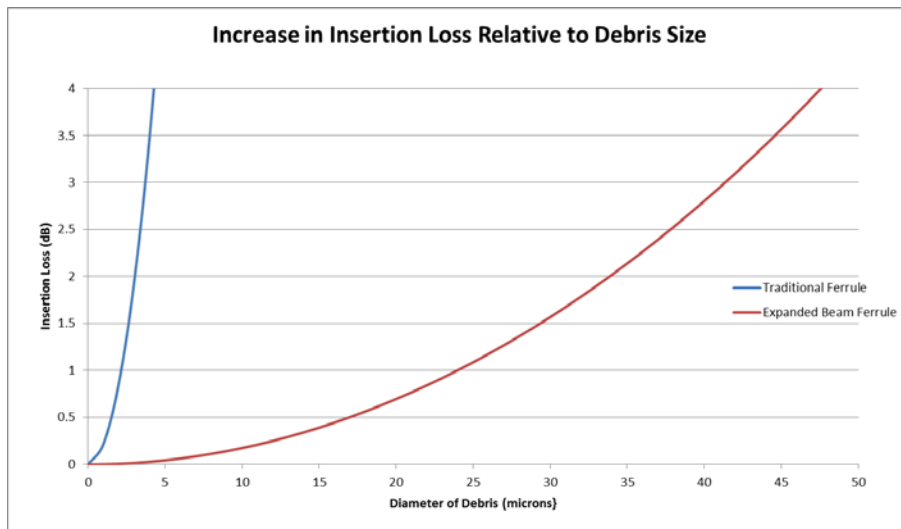


Figure 17: Simulated impact of Debris on expanded beam and traditional, physical contact ferrules

To empirically evaluate the impact of debris on optical performance, clean lens interconnects were first tested for insertion loss. Subsequently, the lenses were intentionally contaminated with debris and then retested for insertion loss. Images of the contaminated lenses were captured prior to both insertion loss tests. Figure 18 illustrates examples of this analysis. For comparison the allowable polished fiber tip defects for traditional, physical contact connectors as defined by industry standards is included.

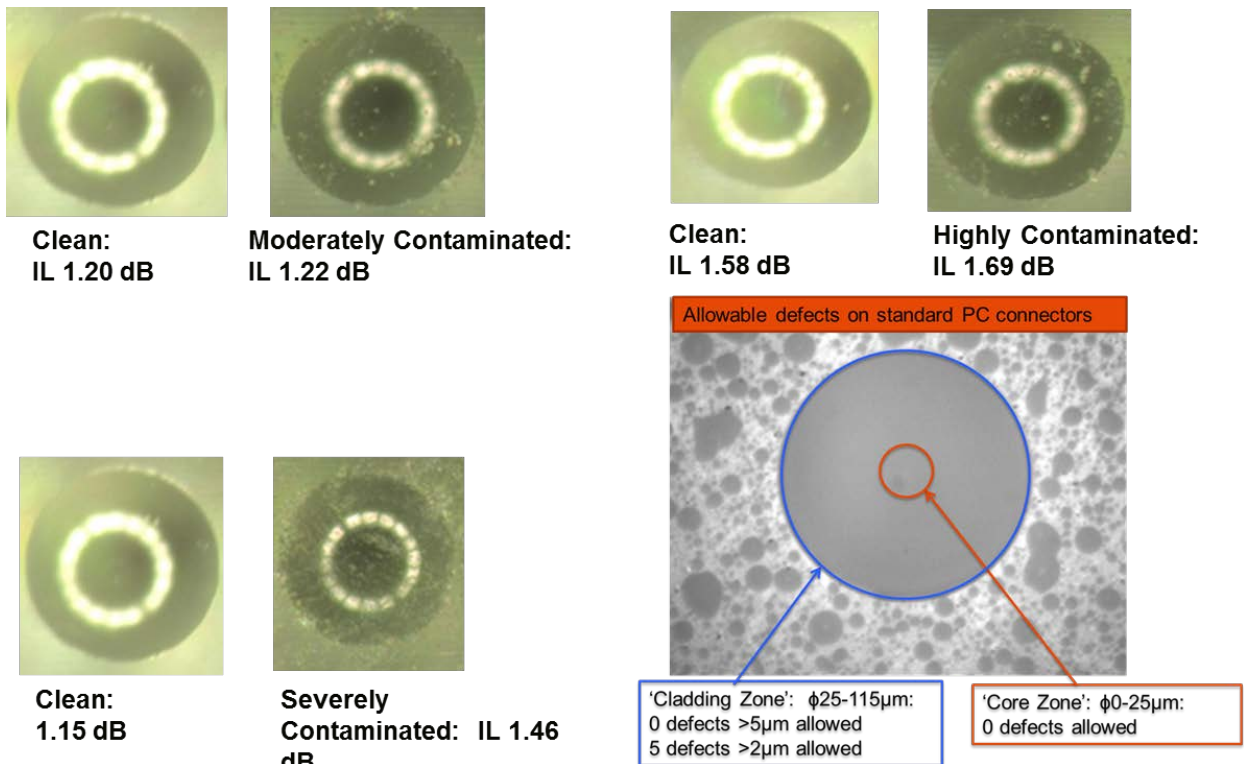


Figure 18: Contamination impact on SM expanded beam interconnect w/ industry standard allowable defects on traditional physical contact connectors per IEC 61300-3-35

8. SUMMARY AND FUTURE WORK

A multi-fiber, molded, monolithic, expanded beam ferrule had been designed, manufactured and tested to confirm the viability of low cost, no-polish, debris insensitive ferrule for singlemode applications. This interconnect technology is ideal for passive interconnects at the equipment, card-edge interface with embedded optic technology where cost, density, debris sensitivity and coupling force are of concern.

Parts were manufactured to the specifications assumed in the optical simulations. Empirical data from randomly mated connector pairs was collected and confirmed to closely match the predicted results from the optical Monte Carlo simulation.

One of the next steps for this interconnect technology to further reduce the insertion loss. This can be accomplished by further tightening the axial and angular alignment tolerances of the fiber holes and lenses relative to the mating alignment features. Furthermore, as highlighted in the Section 5, optical modeling, approximately 0.49 dB of insertion loss is inherent in the system tested. 0.38dB of this loss is due to the lens to air interfaces for the mated ferrules.. By applying an efficient anti-reflection treatment to the lens surface, an improvement in insertion loss of approximately 0.3-0.4 dB can be gained.

In addition to reducing the insertion loss,, this ferrule will be subjected to industry standard, passive, multi-fiber performance qualification standards. For public network applications, the applicable standard is Telcordia GR-1435. For datacenter applications the applicable connector performance standard is the TIA 568 series of cabling standards. In addition, multi-source agreements and/or standardization will be pursued to ensure assurance of supply for future applications.

9. References

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