Expanded Beam & Physical Contact
Fiber Optic Connectors

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I. Introduction

Fiber optic technology is used in ever-increasing applications due to its inherent advantages (lower weight, EMI/RFI immunity, higher bandwidths and distances) over copper. Fiber optic connectors are used to couple the source, receiver and other components to the fiber optic cable. There are many types of fiber optic connectors, but each generally uses either physical contact or expanded beam technology. This paper discusses the operation, types and optical performance of these two approaches and the advantages/disadvantages of each.

II. Physical Contact (PC) Operation

Physical Contact (PC) connections are characterized by the physical mating of two optical fibers. Precision ceramic ferrules are typically utilized for PC connections (see *Figure 1*). A PC connection is accomplished by terminating the optical fiber into a precision ceramic ferrule. Epoxy is used to affix the fiber into the ferrule. The tip of the ceramic ferrule is polished in a precise manner to ensure that light enters and exits at a known trajectory with little scattering or optical loss. Polishing the terminated ceramic ferrule is a critical process in physical contact fiber optic connectors.

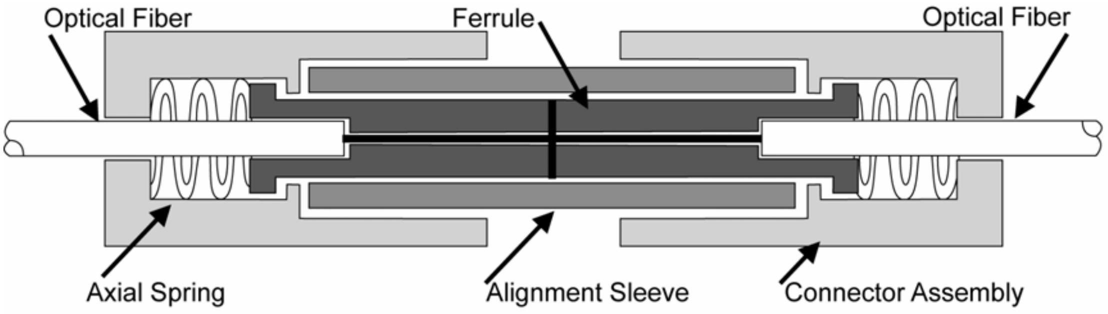

Figure 1: Physical Contact (PC)

Because the optical fibers are touching each other using opposing forces (axial springs), light exits one fiber and enters the other with low insertion loss (IL), typically around 0.25 dB. An alignment sleeve positions the two ferrules, ensuring precise axial alignment. This is the prevalent connection method in the global fiber optic industry.

II.1 Physical Contact Connector Types

Fiber optic interconnect technology has advanced significantly since connectors were first used commercially in the 1970s. Biconic connectors, SMAs with stainless steel ferrules and even plastic lenses were early technologies incorporating fiber optic connectors. Eventually, alternative technologies displaced these initial solutions. Advances in ceramic manufacturing enabled high precision, physical contact fiber optic connectors. Today, there are hundreds of single and multi-channel fiber optic connector types serving numerous industries including datacom, telecom, military, oil & gas, mining, etc.

II.1.1 Single Channel

As previously discussed, PC connectors are characterized by the direct contact of mated, polished fibers using tight tolerance ferrules and alignment sleeves and/or mating pins. This ceramic-ferruled technology exhibits reliable optical performance, with several designs becoming widely used industry standards. Typically, these connectors are single fiber solutions with plastic shells.

Figure 2 shows some of the popular single channel connectors. LC and SC connectors are commonly used in the datacom and telecom industries. FC and ST connectors are becoming less popular but are still used in instrumentation.

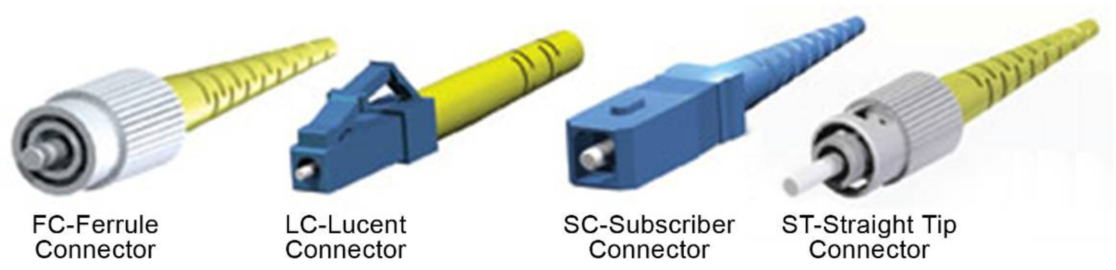

Figure 2: Common Commercial Single Channel Fiber Optic Connectors

Figure 3 depicts LC connector construction. Single fiber connectors vary in construction but in general consist of precision ferrule, spring, connector body and strain relief.

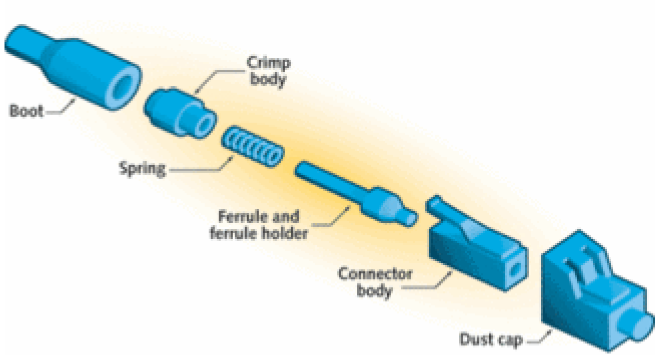

Figure 3: Construction of an LC Connector

II.1.2 Multi-channel

Many applications require multiple fiber optic channels in a single connector to reduce space and facilitate connectivity. Multi-channel connectors house multiple fiber optic termini (*Figure 4*) in a precision insert. The termini can be configured as a pin/socket combination or genderless. As with the single channel physical contact connector, the main components of the termini are the ceramic ferrule, spring and pin body. The insert is then mounted in a metal or composite shell to provide environmental protection (*Figure 5*) and group connectivity.

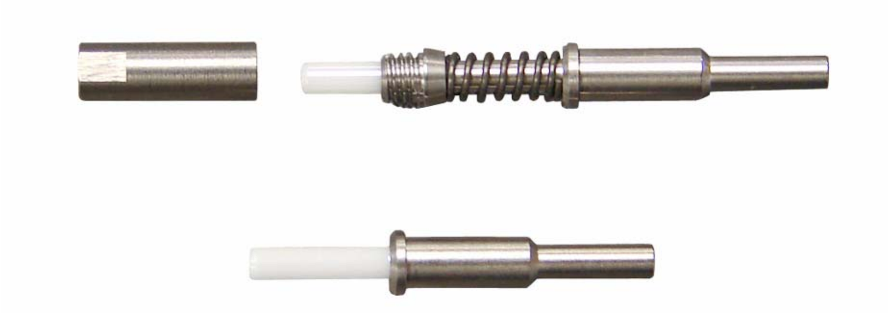

Figure 4: Fiber Optic Contact (M29504/4 & /5)

Figure 5: Multi-channel Fiber Optic Connector (ARINC 801)

Further advances in technology as well as the need for higher density have ushered in a completely new family of commercial interconnect technology. MTP and MPO connectors can terminate with up to 24 fibers in a very small form factor. All of these commercial interconnect solutions use a physical contact form of mating.

II.2 Optical Performance

The two most common connector optical performance parameters are insertion loss and return loss (back reflection). Physical contact connectors provide far superior insertion loss (0.25 dB typically) and return loss (-40 to -65dB depending on the polish) than expanded beam connectors.

II.2.1 Insertion Loss (IL)

The predominant factors contributing to insertion loss for physical contact connectors are alignment, cleanliness, and polish.

II.2.1.1 Alignment

As discussed, physical contact connectivity relies on the precision alignment of the two ferrules housing the fiber and the alignment sleeve, to ensure low insertion loss.

One possible source of high insertion loss in physical contact connectors is end gap separation. End gap separation introduces air into the gap between ferrules, and light spreads beyond the receiving fiber's numeric aperture (*Figure 6*). End gap separation is preventable by employing proper manufacturing termination procedures.

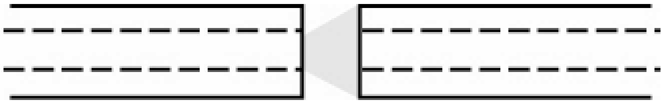

Figure 6: End Gap Separation

The ceramic ferrule itself plays an extremely important role in ensuring low loss connections. The most important dimensions on the ferrule are the outside diameter and finish, the inside hole diameter and the measurement of how accurately centered the inner diameter is in relation to the outer diameter (*concentricity-Figure 7*).

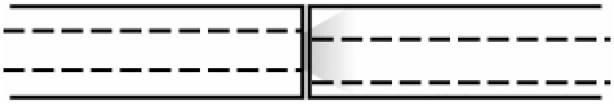

Figure 7: Poor Concentricity

Another potential source of insertion loss is axial misalignment (*Figure 8*). Optical power is lost if the centerlines of the two adjoining fiber cores are not centered. A precision alignment sleeve alleviates this misalignment. Typically, use of a ceramic split sleeve ensures the most precise alignment between two ferrules. Solid sleeves were also used to align ferrules during the past several years. The optical insertion loss is slightly greater for solid sleeves and more rugged.

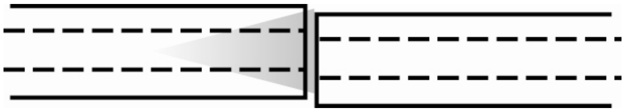

Figure 8: Axial Misalignment

Axial run-out is another possible alignment issue and source for insertion loss (*Figure 9*). The connector assembly must be designed and constructed so that the two fibers are precisely parallel with each other.

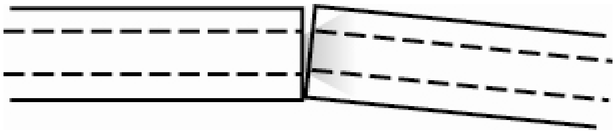

Figure 9: Axial Run-out

II.1.1.2 Cleanliness & Contamination

Due to the small size of the fiber core (9, 50 and 62.5 microns are popular sizes), it is very important that the physical contact interface is clean. The user should inspect and clean fiber endfaces before making connections. Debris and contamination of the connector endface can cause increased insertion loss, back reflection and may damage the fiber. Mishandling can cause contamination (e.g., skin oil, lint, alcohol residue, distilled water residue) or from environmental sources (e.g., dust). *Figure 10* depicts an endface photo with a clean fiber endface and one containing scratches and contaminated with debris.

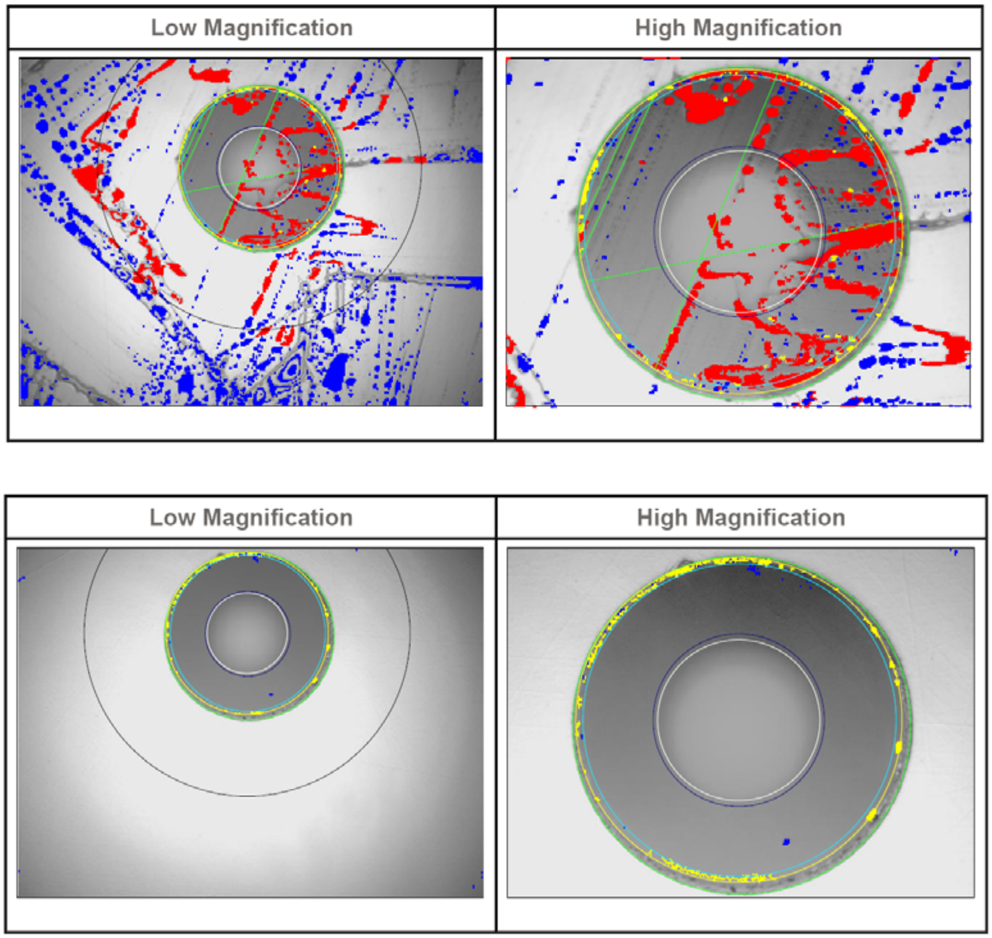

Figure 10: Contaminated (top) & Clean Endfaces (bottom)

II.1.1.3 Polish

The quality of the polish is also critical to ensure low insertion loss in physical contact connectors. Telecordia document GR-326, *Generic Requirements for Singlemode Optical Connectors and Jumper Assemblies*, defines the endface requirements including radius of curvature, apex offset, fiber height, angle, scratches, etc. for the polish. *Figure 11* portrays photos of well-polished and poorly polished endfaces.

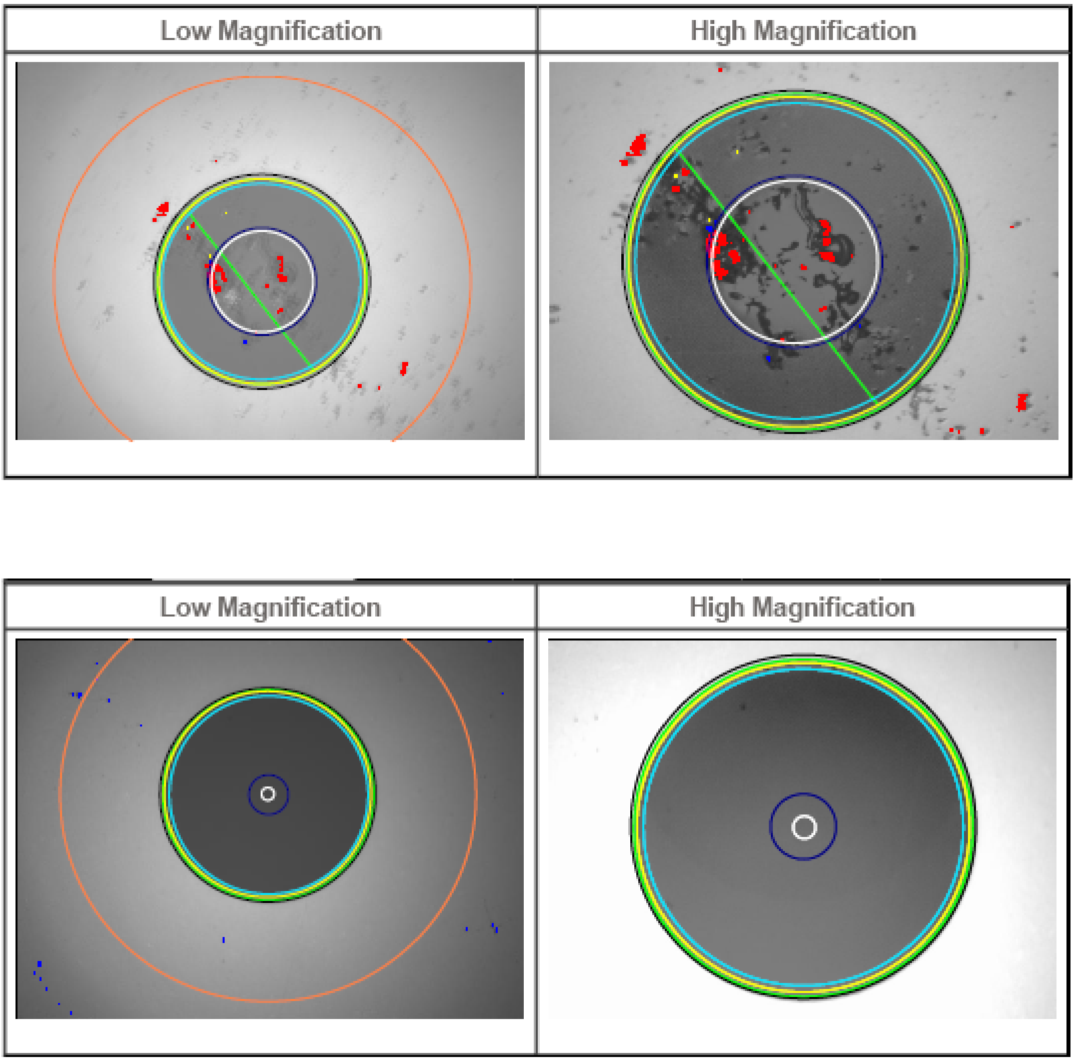

Figure 11: Unacceptable (top) & Acceptable (bottom) Polished Endfaces

II.2.2 Return Loss (RL)

The return loss of the connector is a measurement of how much light is reflected back at the connector interface. The return loss is affected by alignment, contamination and polishing. For example, if the mating faces of the two fibers are not parallel, some energy reflects back to the source. Additionally, contamination at the mating interface causes refection and scattering of light.

One of the most critical factors associated with return loss is polish quality. A poor polish may create an end-gap separation or an end-angle (*Figure 12*). The different refractive indices between glass and air cause Fresnel reflections, resulting in return loss.

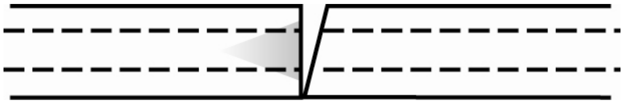

Figure 12: End-Angle

The type of polish also affects the return loss of the connection (*Figure 13*). The flat PC polish eliminates the aforementioned refractive index differences, but any contamination of the outer diameter of the ferrule may affect the integrity of the physical contact of the fibers. This issue is solved by using a rounded PC polish that allows only the fibers to touch, but any reflection that occurs will bounce straight back to the source. By employing an angle polish (APC), any back reflection is directed away from the core and into the cladding. The polish angle for APC termini is typically 8 or 9 degrees.

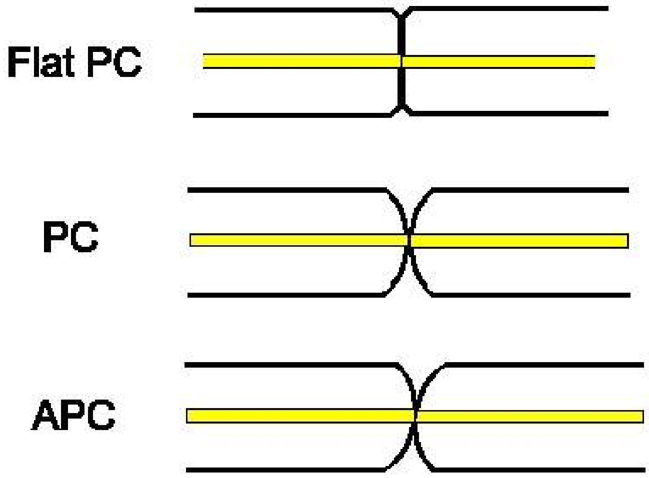

Figure 13: Different Types of Fiber Optic Polishing

An example of a multi-channel APC connector is shown in *Figure 14*. Note that the termini and inserts are indexed to ensure the angled faces are in proper physical contact.

Figure 14: Fiber Optic Multi-channel Connector with Angle Polish Contacts (APC28876)

When the tightest tolerance ceramic ferrules and alignment sleeves are combined with the highest quality termination and polishing procedures, PC connections deliver unsurpassed optical performance.

III. Expanded Beam (EB)

Expanded beam connectors typically use two lenses to expand, collimate, and then refocus the light from the transmitting fiber into the receiving fiber (see Figure 15). The lenses are generally either ball lenses or GRIN (graded index) rod lenses. The ball lens has a constant refractive index and is manufactured using commonly available glasses. The light from the source changes direction at the curved boundaries, and travels through the inside of the lens in straight lines. The GRIN lens has a cylindrical form factor, but the refractive index is not constant. Rather, the refractive index distribution varies radially with a parabolic profile, with the maximum index of refraction along the axis of the lens. Unlike the ball lens, the light curves through the inside of the GRIN lens. Placing a point light source at the focal point of either lens collimates the light.

The use of expanded beam optic interfaces results in reduced signal loss due to contamination at the optic interface. The lens design also facilitates cleaning and because the light path travels over an air-gap, there is no physical contact. Lack of physical contact potentially eliminates the mechanical wear found in physical contact connectors, allowing more connector mating cycles. *Figure 15* shows a typical ball lens expanded beam fiber optic connection system.

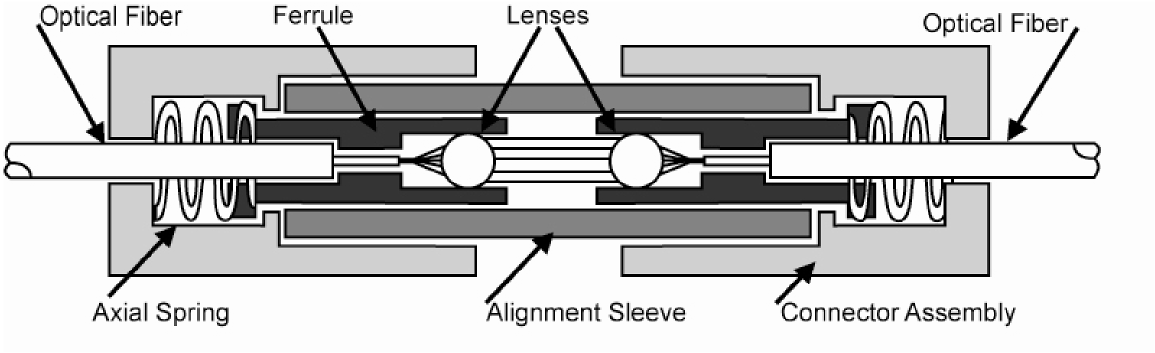

Figure 15: Expanded Beam (EB)

Similar to physical contact connectors, EB connectors typically use precision ceramic ferrules to align the fiber to the lens. As with PC connections, tight tolerance ceramic ferrules are used in conjunction with high quality termination and polishing procedures. The connector shell, or insert, which aligns the ferrule to the lens, becomes the critical subcomponent in enabling a low-loss EB connection. Achieving the tight dimensions necessary for a quality EB insert is required in order keep IL measurements low. Combining precision subcomponents and ceramics with the proper termination and polishing procedures can yield EB connections with consistent IL values less than 1.0 dB.

In general, expanded beam connectors are more expensive to produce, which has limited their use in telecom and datacom applications. However, expanded beam technology is used in several military and commercial applications where frequent mating and unmating may expose the optical interfaces to contamination. Several recently introduced lower cost expanded beam connectors are targeted at commercial medical applications, where reliability and thousands of mating cycles are required.

III.1 Expanded Beam Connector Types

While expanded beam connector products are not as diverse as physical contact connectors, there are multiple types of expanded beam connectors. *Figure 16* portrays an expanded beam contact used in multi-channel connector shells. *Figure 17* depicts a multi-channel expanded beam connector using a monolithic insert.

Figure 16: Expanded Beam (EB) Contact

Figure 17: Expanded Beam (EB) Multi-channel Connector

III.3 Optical Performance

III.3.1 Insertion Loss

As previously stated, there is marked disparity between PC and EB connections in terms of IL. Systems engineers need to be aware of this when designing optical subsystems. In many cases, this difference in insertion loss performance is inconsequential. In others a connector specification may dictate whether PC or EB connectors can be utilized.

III.3.1.1 Alignment

Misalignments cause increases in insertion loss for EB connectors. While fiber separation is less critical in expanded beam coupling, EB connectors are extremely sensitive to lateral misalignment and angular misalignment.

III.3.1.1.1 Lateral Alignment

The lateral alignment of the fiber to the lens is critical. Small misalignments of the terminus with respect to the optical axis of the ball lens can effectively steer the beam off axis. The beam may remain collimated, but the focus will shift in the receiving fiber. *Figure 18* shows that the insertion loss deteriorates significantly, as the terminus/fiber is laterally moved away from the optical center axis of the ball lens. This model predicts that even a miniscule misalignment of 2 microns is enough to cause a 1.0dB loss. As a result, connector manufacturers must achieve ultra-precision manufacturing tolerances in expanded beam connector manufacture and construction.

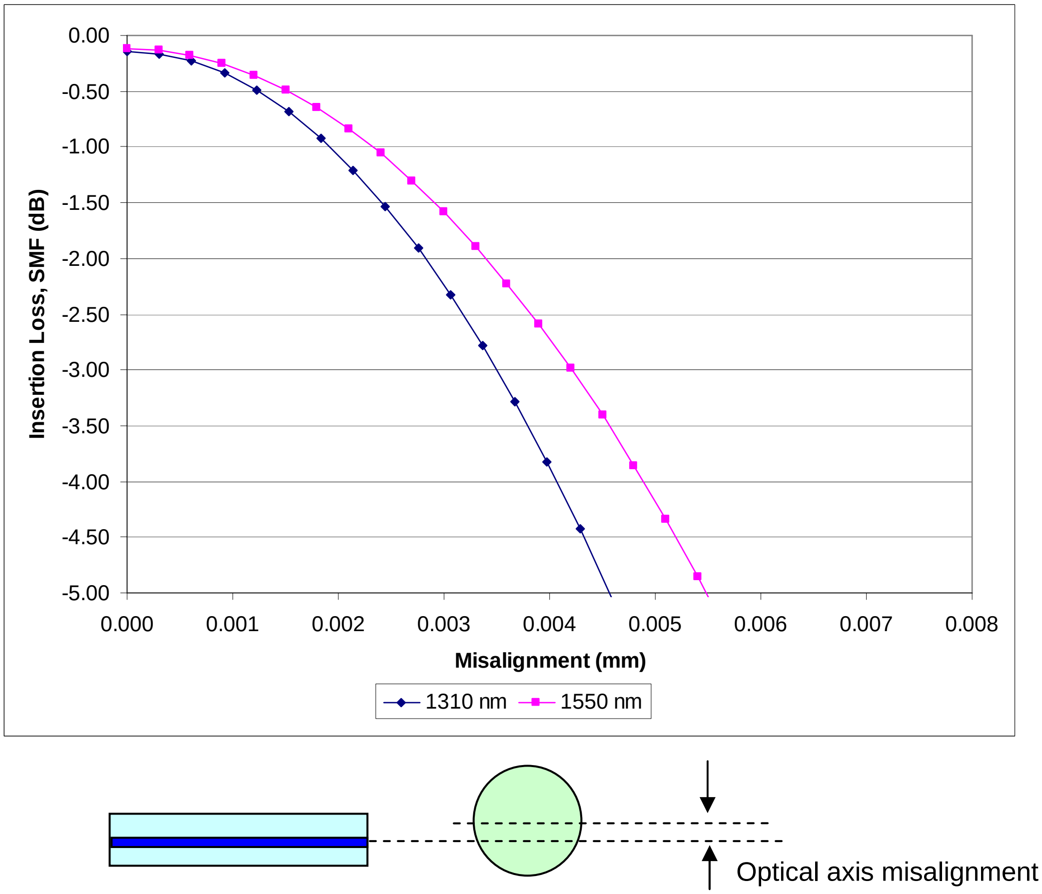

Figure 18: Insertion Loss vs. Fiber-to-Lens Lateral Misalignment

III.3.1.1.2 Angular Alignment

Angular misalignment results from a collimated beam that is pointing off-axis, a mating plane that is non-planar, or a contaminant that is present between the mating interfaces. *Figure 19* shows the relationship between connector-to-connector tilt and insertion loss; it can be inferred that this data also shows the effect on a collimated beam that is pointing off-axis. The data indicates that tilts in the system greatly affect the insertion loss of the connection. This data can also infer the accuracy needed for the perpendicularity of the beam. The analysis shows that a mere .08-degree deviation will induce a 1.0dB loss. This is equivalent to a gap at one point in the mating plane of 0.018 mm that prevents the inserts from fully mating.

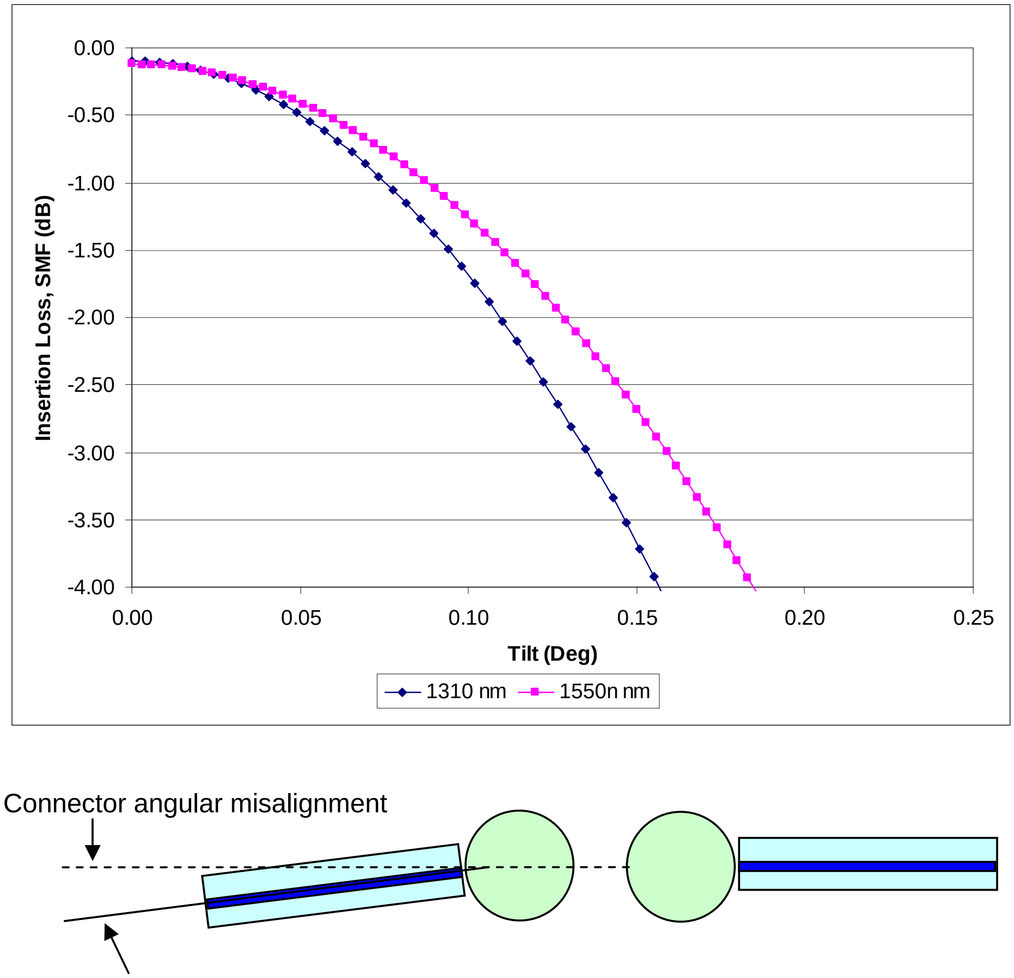

Figure 19: Insertion Loss vs. Connector Angular Misalignment

III.3.1.2 Cleanliness & Contamination

Because EB connectors expand the light beam across the interconnect point, the impact of debris on the lens surface, such as dirt and dust particles, is minimized when compared with PC connections. However, while PC connections push away moisture and liquids during mating, thus eliminating its impact on performance, EB connections react differently to moisture and liquids. Moisture or liquids on the lenses can degrade performance by scattering the light as it tries to pass through the contaminant.

III.3.1.3 Polish Quality

Similar to PC connectors, EB technology typically uses a precision ceramic ferrule for the fiber to lens interface. In order to minimize the insertion loss, the same care and procedures used for PC connectors must be utilized for EB technology.

III.3.2 Return Loss

Expanded beam technology typically has an inherent shortcoming in regard to return loss. Light traversing between materials with different refractive indices (i.e. glass to air interface) will be partially reflected, resulting in increased insertion loss and high return loss. Polishing techniques and anti-reflection (AR) lens coatings can address some of the reflective characteristics of EB connections, but the air gap inherent in EB technology typically limits RL performance to 50 dB. Additionally, the use of anti-reflection coatings limits the wavelengths that the expanded beam connector can support, whereas PC connectors are wavelength independent.

IV. Comparison of PC vs EB Technology

Table 1 summarizes various performance parameters for the two technologies.

	PC Connectors				**EB Connectors**			
Performance Parameter	**P**	**A**	**G**	**E**	**P**	**A**	**G**	**E**
Insertion Loss (MM)				X			X	
Insertion Loss (SM)				X		X		
Return Loss				X		X		
Debris Susceptibility	X							X
Moisture Susceptibility				X	X			
Wavelength Independence				X	X			
Mate/Demate Cycles			X					X
Termini Density				X		X		
Environmental Performance				X			X	

P=Poor; A=Average; G=Good; E=Excellent

Table 1: Summary Table for PC vs EB Connectors

- **Optical Performance (IL and RL):** PC technology has the clear advantage in this category. For PC technology, typical insertion loss and return loss (APC) are 0.3dB and -65dB, respectively. For EB connectors, typical insertion loss numbers are 1.5dB and -30dB, respectively. Thus, physical contact connectors are the clear choice for those systems with limited link budgets and those requiring low back reflection (e.g., analog systems).

- **Environmental Performance:** Mechanical shock, vibration and temperature extremes can successfully be addressed through connector designs that minimize the impact of these external environmental factors. PC and EB technologies in and of themselves show very little variance between how each performs optically when subjected to these elements.

- **Wavelength Independence:** As previously discussed, the AR coatings that help reduce the return loss in expanded beam connectors also serve to limit the wavelengths supported by the connection. Physical contact technology is the preferred choice for designs incorporating wavelength dynamic or broad spectrum (i.e. wavelength division multiplexing) sources.

- **Debris and Moisture Susceptibility:** Susceptibility to contamination affects optical performance of PC and EB in different ways, depending on the contaminant. Because EB connectors expand the light beam across the interconnect point, the impact of debris such as dirt and dust particles is minimized in comparison to PC connections. Moisture also affects PC and EB differently. PC connections push away moisture during mating, eliminating its impact on performance. Moisture on the EB lenses, however, can degrade performance by scattering the light as it tries to pass through the contaminant. Best practices would dictate that connector cleanliness maintenance is performed routinely, regardless of the connector technology deployed.

- **Density:** Due to smaller size ferrules and termini spacing, physical contact connectors usually have an advantage over EB connectors, particularly in high channel count connectors.

- **Cost:** On a cost per channel basis, and frequently for overall connection and connector costs, expanded beam connectors are higher-priced than physical contact connectors.

- **Ease of Cleaning:** Overall, it is easier to clean expanded beam connectors than PC connectors. Windowed EB connectors are quite easy to clean and dry. Users must be careful when cleaning around lenses because contamination may be pushed into the small cavities surrounding the ball lenses.

- **Hydrocarbons:** Hydrocarbons can present a challenge for cleaning fiber endfaces and for cleaning expanded beam connectors. Solvents are often employed, making this task somewhat easier, but a film can remain following cleaning. Special fabrics and materials make cleaning these types of contamination easier.

- **Mate/Demate Cycles**: By virtue of the airgap inherent in EB technology, this type of connection allows a greater number of mate/demate cycles than PC technology.

Conclusion

Systems engineers must fully educate themselves in regard to PC and EB connector technologies. In harsh environment applications, standards have been developed utilizing both types of solutions. End users will demand adherence to these standards. In some cases, end users will demand adherence to a particular technology. The engineer must know the differences between the two types of connectors. Successful connector designs can minimize the aforementioned weaknesses, but differences between PC and EB solutions remain.

About the Authors

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Company Overview

Amphenol Fiber Systems International (AFSI), a division of Amphenol, provides reliable and innovative fiber optic interconnect solutions that withstand the harsh environments of military (ground systems, avionics, and shipboard), energy and broadcast applications. After nearly two decades in business, AFSI maintains its position as a global leader in fiber optic interconnect components and systems such as termini, M28876, 38999 assemblies, MIL-ST, TFOCA and the TFOCA-II® connector, which AFSI developed and patented. AFSI has delivered millions of fiber optic connectors in more than 34 countries. Whenever there is a need for superior cost-effective fiber optic systems and products that will stand up to demanding operating environments, you can rely on AFSI for engineering expertise, top-quality products and expert technical support.

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