White Paper 01-06: *Expanded Beam versus Butt-Coupled Connectors*

Abstract:

When it comes to the design of fiber optic connectors for harsh environments, two schools of thought dominate the market: Butt-Coupled or Expanded Beam Designs. Each approach has its own advantages and disadvantages and the choice of the 'best' connector can be blurred by the specifics of the application environment and unique requirements of the systems design. In this white paper, we explain the difference between these two technologies and present the basis of a systems engineering design guide to assist in the specification of reliable and cost effective fiber optic connectors for harsh environment applications including: Tactical, Shipboard, Aerospace, Geophysical, Railway, Video Broadcast and Power Generation. Key topics of this design guide include: Insertion and Return Loss, Mating Durability, and sensitivity to Thermal and Mechanical extremes.

Introduction

Due to their added cost, performance and reliability impact, most systems engineers regard fiber optic connectors as a necessary evil to support installation, service or concatenation of cable segments in order to field longer haul installations too impractical to field otherwise. We can not fault this opinion since early attempts at fielding commercial-grade fiber optic connectors into non-plant environments yielded mean-time-between-failures orders of magnitude worse than the fiber cable itself! The principal failure modes of these early attempts at fielding fiber optics into harsh environments came down to three principle areas: (1) inadequate isolation of external stresses and strains from effecting the optical alignment; (2) fiber bonding failure; and (3) environmental contamination of the optical surfaces. Successful (marketable) solutions to these three problem areas also needed to satisfy budgetary constraints: both optical power and financial budget!

Butt-Coupled Connectors

The harsh environment connectivity market has settled down to two distinct approaches: Butt-Coupled or Expanded Beam. Fiber optic butt-coupled connectors align and bring specially prepared ends of two fibers into close contact. An early solution to the special requirements of harsh environments, was the biconical connector depicted in Figure 1.

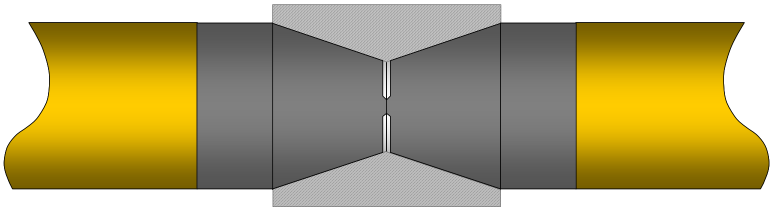


Figure 1. Biconical termini are brought in close contact, but by design and manufacturing technique, are not intended to bring the fiber endfaces in physical contact.

Biconical connectors rely on the engagement of the conical end of the termini to engage into a corresponding conical alignment sleeve. Inasmuch as the respective conic sections are of the same angle and possess carefully controlled diameters and the termini are polished to proper length, the mated fiber end-faces do not come into physical contact. From the perspective of minimizing the potential of intervening contaminants from permanently damaging the optically polished endfaces of the fiber during mating, the biconic connector enjoyed initial acceptance as a multi-terminus, tactical connector dubbed TFOCA (Tactical Fiber Optic Connector/Cable Assembly). However, the biconic method of precision alignment does have an Achilles heel in that contamination of either of the conic surfaces can lead to gross misalignment of the butt-coupled fibers as illustrated in Figure 1. As we shall see in the Insertion Loss section of this paper, lateral and longitudinal misalignment dominates the principal loss mechanisms of butt-coupled optical connectors.

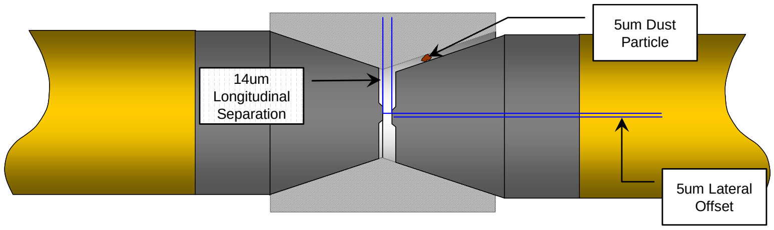


Figure 2. Minor contamination of biconic surfaces can lead to significant lateral and longitudinal offset and in turn, excess insertion loss.

To solve the problem of contamination dependent misalignment and the reflection loss associated with the air-gapped biconical connector, cylindrical ferrule designs came into favor wherein precision alignment was achieved by aligning to the outer diameter of the cylindrical ferrules using an interference-fit alignment sleeve as shown in Figure 3. Without the physical hard stop provided by the geometry of the conic section, the mated fibers of this type of butt-coupled connector come into physical contact. As such, this class of butt-coupling is known as physical contact coupling. Physical contact or PC termini, as they've come to be known, purposefully have their termini endfaces polished with a spherically convex end to 'squeeze out' any intervening air. This is done to ensure a glass-to-glass contact to minimize reflective losses (Return Loss) that would otherwise result from the index of refraction (speed of light) mismatch imposed by the glass-to-air interface of the mated joint.

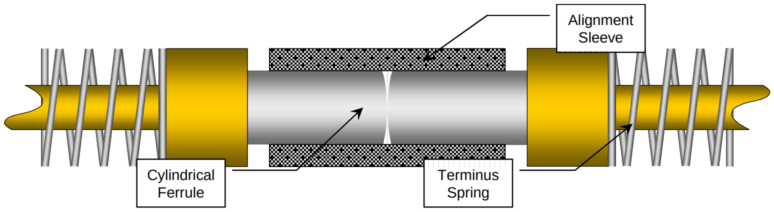


Figure 3. Cylindrical ferrule butt-coupled connector features an interference-fit alignment sleeve for robust fiber-to-fiber alignment.

At first blush, bringing two precision and optically polished glass surfaces together into intimate contact seems to be counter-intuitive to establishing a reliable connection for harsh environments. However, owing to the compressive strength of glass and the fracture toughness of the ceramic ferrules, studies have shown these types of connectors can lead to highly reliable connectors for high dynamic environments (mechanical shock and vibration) just as long as the terminus spring is adequately sized to ensure the ferrule endfaces never move apart as a result of high accelerations.

Expanded Beam Connectors

The durability of cylindrical butt-coupled connectors, for all of their improvement in performance over that of biconical connectors, is still very much dependent upon the discipline of the operator to ensure the termini endfaces are cleaned prior to mating. In the DoD environment, the discipline and training levels of most military personnel and its subcontractors is such that cleaning prior to mating optical connectors is almost second nature. However, for some industries or environments in which cleaning of the optical connector is impossible and/or the reliance on the discipline of the field operators is impractical, expanded beam connectors may prevail.

By its name, an expanded beam connector relies on a pair of lenses to collimate the light emerging from a fiber and on the receiving end, focus the collimated light onto the end of the second fiber. The collimated beam can now bridge an air gap measured in millimeters without incurring undue optical loss. In this way, durability issues of mating a dirty physical contact can be avoided by virtue of the "stand-off" distance afforded by the collimated beam.

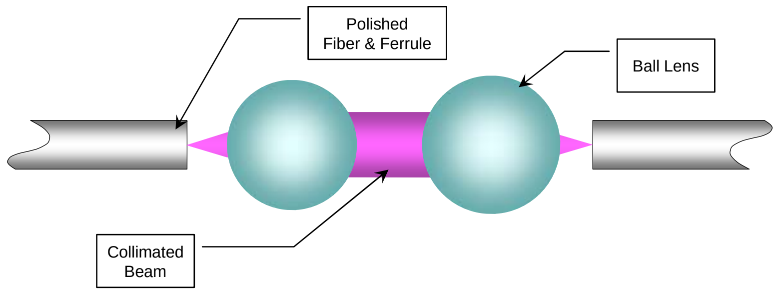


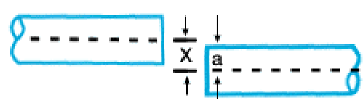
Figure 4. Expanded beam connectors utilize lenses to collimate and refocus the light from one fiber to the other as a means of eliminating the potential for damage to the termini endfaces as a result of mating contaminated physical contact termini.

Unfortunately, as we'll discuss in the sections that follow, the robustness to contamination afforded by the expanded beam connector does come at some expense to both optical power and financial budgets.

Insertion Loss Mechanisms

As with any "optical system", performance optimization of an expanded beam connector will require design trade-offs between such things as lens focal length, lens index and dispersion, anti-reflection coatings and spherical aberration, to name just a few. Most of these topics are beyond the scope of this paper and will only be touched on for comparison purposes only. Aside from these nuances, both physical contact, (PC), and expanded beam, (EB), connectors, will be affected by three theoretical optical loss mechanisms: lateral offset, angular tilt and longitudinal separation. For purposes of simplicity (so as to avoid a lengthy discussion of modal distribution and its impact on coupling loss), we discuss each of these loss mechanism from the perspective of the more stringent requirements of coupling single mode fibers.

Lateral Offset and Mating Durability



$$L_{lat} = -10\log\left[e^{-u^2}\right], \text{ where } u = \frac{x}{\omega_0}$$

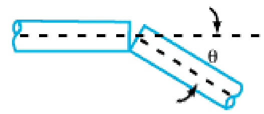
By far, lateral offset is the leading loss mechanism for PC fiber connectors. For example, a singlemode fiber with a fundamental mode radius, (ω_o = 4.5μm) and a lateral offset of only 1.6μm, will lead to an insertion loss of 0.5dB! That insertion losses of 0.5dB and 0.75dB are now considered the maximum acceptable loss for both simplex and multi-terminus PC connectors, respectively, speaks volumes to today's manufacturing control of concentricity run-out of ceramic ferrules and fiber drawing, not to mention the diameter control of both fiber and ferrule drilling! For EB connectors, the impact of lateral misalignment at the mating plane of two mated EB connectors on insertion loss, goes inversely with magnification of the beam diameter. For a typical EB connector utilizing a 3mm diameter ball lens, the collimation diameter of the beam is increased approximately 45 times. With ω_o increased to 200μm, the EB connector accommodates nearly 70μm (0.0027") of lateral misalignment before the connector experiences 0.5dB of insertion loss!

The EB connector's immunity to lateral offset losses of EB connectors afforded by the magnification of the lens is a two-edged sword. Inasmuch as the impact on insertion loss is relaxed at the mating plane of the EB connector, it comes at the expense of the positional tolerance of the fiber. From the example above, a lateral offset of the fiber by 1.6μm will result in a lateral offset of the collimated beam of 70μm which translates to an insertion loss of 0.5dB! This high degree of positional accuracy of the fiber requires that the stainless steel EB insert needs to be machined to micron tolerances. The cost of the precision insert plus the added expense of the ball lenses can add 40% to the cost of an equivalent PC connector.

On the up side, shifting the high tolerance machining requirements from the mating plane of the EB connector, (the location most prone to wear in high mating cycle applications), to the comparative dimensional stability internal to the connector insert, can yield a connector with greater mating durability than what can be achieved with PC contact termini. The current state of the art for PC termini, is 2,000 mating cycles before increases in insertion loss exceed 0.5dB. For EB connectors, mating durability as high as 5,000 mating cycles has been reported.

Angular Misalignment

From L_{ang} for single mode fiber, we note that for all the improvement in lateral offset loss immunity afforded by the EB connector, this comes at the expense of increased sensitivity to angular misalignment. This is because as the lens collimates the expanded beam, the numeric aperture (the divergence angle) approaches zero. If we imagine the emerging beam from the EB connector as a well collimated or low divergent headlight, the chance of coupling this optical energy into the headlight of an oncoming car will be critically dependent on the aiming (angular misalignment) of the headlamp.



$$L_{ang} = -10\log\left[e^{-T^2}\right], \text{ where } T = \frac{n_0 \pi \omega_0 \sin\theta}{\lambda}$$

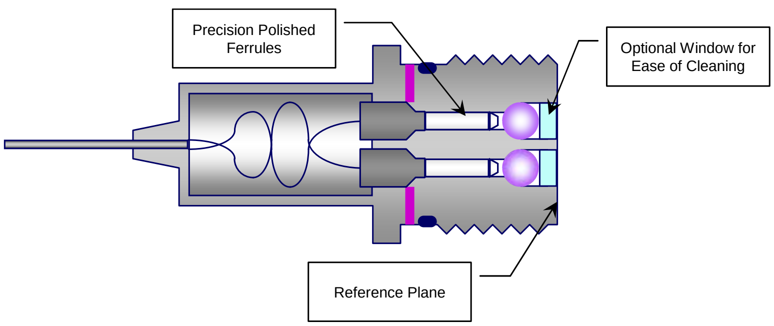


Figure 6. Schematic of multi-terminus EB connector showing optional windows for enhanced ease of cleaning and the reference plane for control of angular misalignment.

As with the headlamp example, critical angular alignment of EB connectors is provided by a reference plane or raised lip on the EB insert as shown in Figure 6. To ensure the reference plane is isolated from external bending moments applied to the mated connector pair, the insert is axially held in place by a compliant support such as an ‘o’-ring. The inserts are preloaded longitudinally with a wavespring of adequate spring force to ensure the two mated inserts always remain in contact during exposure to high accelerations resulting from mechanical shock or vibration. For high shock loads in excess of 1,000g’s (MIL-STD-901), specifying a spring that can resist this level of reactive force of the substantial mass of the insert can be problematic. Although, the optical surfaces, by virtue of their not being in contact will not be damaged, inadequate longitudinal restoring forces can result in

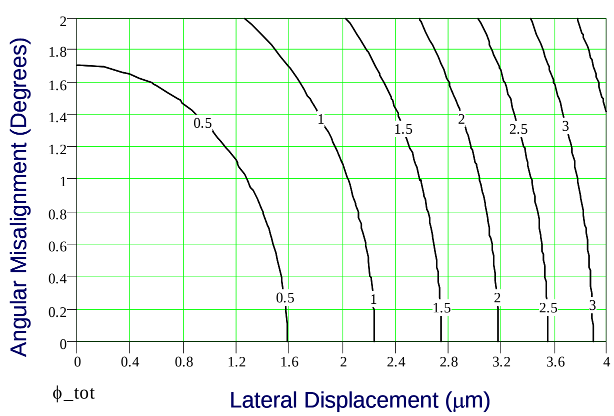
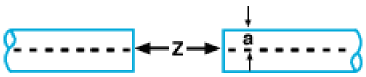


Figure 5. Insertion loss of single-mode optical connectors as a function of angular misalignment and lateral displacement.

optical discontinuities if the two reference planes tilt with respect to each other during the dynamic event.

The potential for poorer dynamic performance as compared to the PC contact termini notwithstanding, proper cleaning of the reference plane or lip is important to ensuring optimum performance of the EB connector. From Figure 5, we see that a single-mode PC termini with 0 lateral offset and 1.7^{o} angular misalignment, will exhibit an insertion loss of 0.5dB. For an EB connector, the angular misalignment sensitivity will increase with magnification or from the example used above, a factor of 45. From this, we anticipate a 0.5dB insertion loss for an EB connector undergoing an angular misalignment of just 0.038^{o} (0.7mRadian). For an insert reference lip of ½" diameter, this magnitude of angular misalignment can occur by entrapping a contamination particle measuring a mere 0.0007" (17μm)! Unfortunately, by virtue of the very robustness of the optical surfaces of EB connectors, the importance of cleaning of the reference plane of EB connectors is a topic that tends to be overlooked.

Longitudinal Separation



$$L_{long} = -10\log\left[\frac{1}{Z^2+1}\right], \text{ where } Z = \frac{z\lambda}{2\pi n_0 \omega_0^2}$$

The last of the three loss mechanisms, and perhaps the least debilitating, is longitudinal separation, L_{long}. From the expression for L_{long}, we see that longitudinal separation loss goes inversely as the square of the beam diameter. Clearly, EB connectors win out here. In fact, we include the discussion of longitudinal loss here in so much as to explain the obsolescence of the biconical connector in favor of the physical contact terminus. Using the tolerances for fiber length control for manufacture of biconical connectors, L_{long} predicts an excess loss of 0.7dB for the separation contribution to insertion loss. As we shall discuss in the sections that follow, it was ultimately reflections (Return Loss) that signaled the end for air spaced butt-coupled connectors.

Return Loss.

When light passes from glass to air or vice versa, a portion of the light reflects back into the first medium. This phenomenon is called a Fresnel reflection and results from the difference in index of refraction between glass and air. If the glass has a refractive index of 1.5 and air is 1.0, the Fresnel reflection loss given by $L_{Fresnel}$, for a single glass/air interface is 0.17dB**.**

$$L_{Fresnel} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

For an air spaced butt-coupled connector, the Fresnel loss at the interface of two fibers is twice this or, 0.34 dB. Properly prepared PC contact connectors do not have this problem owing to the glass-to-glass interface.

A review of an expanded beam connector as depicted in Figure 6, reveals the potential of between 3 and 5 such reflections depending on whether or not the optional window is used. STRAN expanded beam connectors do not incorporate this additional window since this window has been shown to experience condensation on the interior window surface which can lead to high insertion loss. With the windows removed, the total Fresnel loss of a mated pair of EB connectors can therefore be 6 x 0.17 or 1.02dB. A specialized anti-reflective coating is applied to the lenses which virtually eliminates the reflections at these surfaces allowing the total Fresnel reflection loss to be reduced to just the reflections originating from the two fiber/air interfaces, or 0.34dB.

For many singlemode applications, spurious reflections from air-spaced fibers can lead to frequency and amplitude instabilities of laser sources or the reduction of signal quality for sensing systems. These applications require a low reflectance or high Return Loss connector. Return Loss. By convention, L_R is always a positive value and is given by:

$$L_R = -10 \cdot \log\left(\frac{P_R}{P_T}\right)$$

For single-mode applications, the fiber can be angle polished to prevent Fresnel reflections from being coupled back down the waveguide. For EB connectors, this technique can achieve L_R's on the order of 40dB with the anti-reflection coatings on the ball lenses becoming the performance pacing item. On the other hand, for angled PC contact connectors, L_R is routinely above 65dB. It should be noted, in spite of angle polishing for control of L_R, the Fresnel reflections still contribute 0.34dB to the total insertion loss for EB connectors.

Adhesive Requirements

Our final topic of significant design considerations between PC and EB connectors, is the topic of adhesive selection. The optical performance and ultimate reliability of both connector types is strongly dependent upon the stability of the adhesive used to bond the fiber into a precision ceramic ferrule. Although, many different adhesives and techniques (including soldering and brazing) have been used over the years, epoxy is still by fair the dominant adhesive of choice. For harsh environments involving temperature extremes, the figure of merit for adhesive selection is dominated by selection of the highest possible Glass Transition Temperature, T_g. For amorphous materials such as adhesives, T_g is the point at which the adhesive looses significant strength as a function of temperature.

For PC termini, wherein the shear force applied to the fiber bondline routinely exceeds 1,000psi, operation above T_g will cause the fiber to pushback and the ensuing air gap can give rise to poor L_R performance. For this reason when fielding a Return Loss sensitive optical link into an environment with temperatures approaching the epoxy's Tg, angle polished termini are strongly encouraged.

And though EB connectors do not have to contend with the high shear stresses of the PC termini, operation above T_g can cause the fiber to piston either in or out due to the coefficient of thermal expansion tripling above T_g. As the fiber moves longitudinally with respect to the lens, the coupling efficiency is negatively affected. Fiber pistoning as small as 25μm can lead to increased loss of 0.3dB. For this reason, STRAN uses adhesives with T_g of 125C and 150C, depending on the fiber type and the environmental requirements.

Summary

By way of a summary of the issues brought to the fore in this paper (and for those issues space did not allow) the Trade Matrix below attempts to contrast the key design issues facing today's systems engineer.

Butt-Coupled versus Expanded Beam Multi-Terminus Connector Selection Trade Matrix for Harsh Environments (Specification / Typical Performance)				
	Butt-Coupled		Expanded Beam	
Parameter	Multi-Mode	Single-Mode	Multi-Mode	Single-Mode
Insertion Loss	0.75/0.30dB	0.75/0.35dB	1.3/1.0dB	1.5/1.0dB
Return Loss	30/35dB	40/52dB	NA/15dB	30/42dB
Mating Durability	500 – 2,000 mates		500 – 5,000 mates	
Cleanability	OK	Care Required	Robust	OK
Connector Density	Moderate	Moderate	Low	Low
Field Maintainable	Y	Y	N	N
Normalized Cost	100%	110%	140%	160%