Single Fiber Fusion Splicing

Application Note

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Scope

This application note describes fundamental theory and applications behind optical fiber splicing for mechanical and, in particular, fusion spliced joints. Various fiber preparation, alignment, splicing and testing methods are discussed, as well as safety precautions and troubleshooting.

General

Splicing often is required to create a continuous optical path for transmission of optical pulses from one fiber length to another. The three basic fiber interconnection methods are: de-matable fiber-optic connectors, mechanical splices and fusion splices. De-matable connectors are used in applications where periodic mating and de-mating is required for maintenance, testing, repairs or reconfiguration of a system. The penalty for this flexibility is the larger physical size and higher cost, as well as higher losses of optical power (typically 0.2 to 1 dB) at the connector interface.

Mechanical splices are available for both multimode and single-mode fiber types and can be either temporary or permanent. Typical mechanical splices for multimode fiber are easy to install and require few specialized installation tools. Insertion loss, defined as the loss in optical power at a joint between identical fibers, typically is 0.2 dB for mechanical multimode splices.

Since single-mode fibers have small optical cores and hence small mode-field diameters (MFD), they are less tolerant of misalignment at a joint. Consequently, mechanical splices capable of achieving acceptable performance within a single-mode system loss budget are somewhat more expensive to purchase and more time consuming to install. Typical insertion losses for single-mode mechanical splices range from 0.05 to 0.2 dB.

Single fiber fusion splicing is one of the most widely used permanent methods for joining optical fibers. Obtaining good fusion splices is much easier today, due to continued improvements to the fusion splice equipment, procedures and practices, in addition to the evolutionary improvements in controlling optical fiber geometries. As a result, losses below 0.05 dB are readily achievable when splicing single-mode fibers of the same product.

Although the economics associated with any particular fiber splicing technology vary with splicing environment, loss budgets, craft skill level and other system parameters, fusion splicing remains the most widely used technique: either single or mass and with active or passive alignment techniques.

The following sections of this application note specifically address the single fiber fusion splicing method. However, many of the areas discussed below - for example, loss factors, fiber preparation, fiber alignment and testing - are common both to mechanical and to fusion splicing techniques.

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Factors Affecting Splice Quality

A high-quality fusion splice is measured by two parameters:

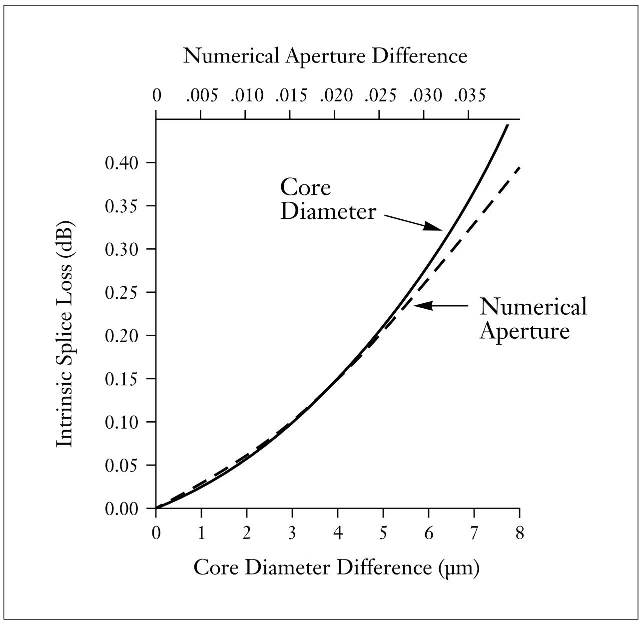
1) Splice loss; and
2) Tensile strength.

Splice Loss Factors

Factors that determine loss in any fiber-joining method can be classified as intrinsic and extrinsic. Intrinsic, or fiber-related, loss factors are determined when the fiber is manufactured, and therefore are beyond the control of the individual doing the splicing.

For graded-index multimode fibers, the fiber related factors include core diameter mismatch, numerical aperture (NA) mismatch, index profile mismatch, and core/cladding concentricity error. Splice loss attributed to core/cladding concentricity errors can be reduced by using a splicing technique that aligns the fiber cores at the joint. The theoretical intrinsic splice loss may be estimated for the major contributors (core diameter and NA mismatch) from Figure 1.

Intrinsic Splice Loss Due to Core Diameter and NA Mismatch
Figure 1

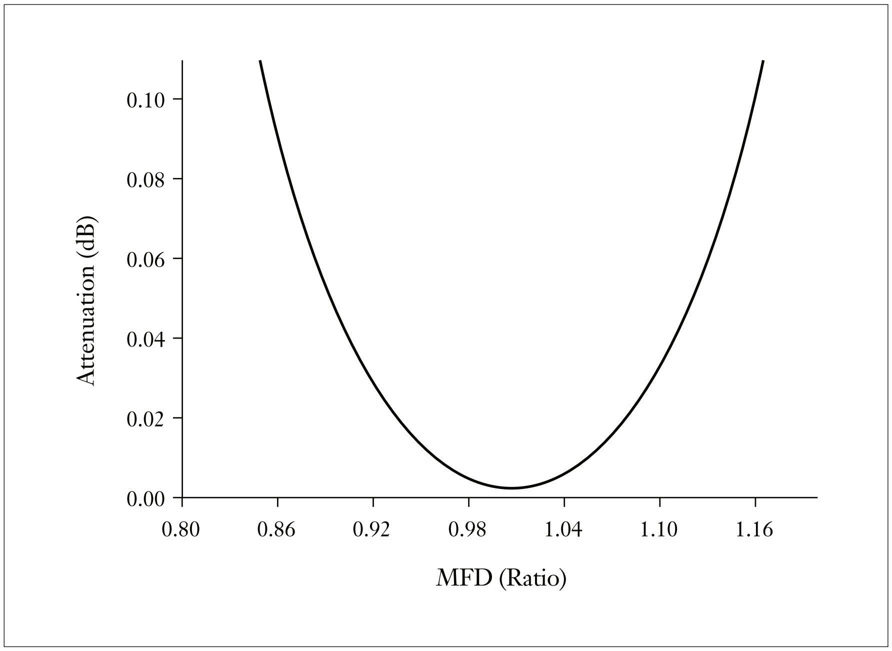


Note that the splice loss is directional with regard to these variables, i.e., loss occurs only when optical propagation is across a joint in which the receiving fiber has the smaller core diameter or NA. Splice loss values are additive, so if two multimode fibers that display mismatches in both core diameter and NA are joined, then their contribution to intrinsic loss is the sum of the two losses.

For single-mode fibers, the dominant fiber-related factor is MFD mismatch. The intrinsic loss contribution due to MFD mismatch may be estimated from Figure 2.

Single-mode Intrinsic Splice Loss Due to MFD Mismatch

Figure 2



As shown in Figure 2, the actual splice loss (bi-directional average when measured by OTDR) is practically non-directional, (e.g., similar fiber-related loss will be seen across the joint regardless of the direction of optical propagation). Also, the intrinsic loss is relatively low for MFD mismatches expected within typical manufacturer's tolerances. For example, the worst-case, fiber-related bi-directional loss for fibers having a 9.2 ± 0.4 micron MFD specification would be approximately 0.03 dB.

Extrinsic, or splice process-related, factors are those induced by the splicing methods and procedures. Splice process factors include lateral and angular misalignment, contamination and core deformation. They can be controlled or minimized by the skill of the individual doing the splicing, and by the automated fiber alignment and fusing cycles on newer equipment. Additional splice process factors exist for mechanical (butt-spliced) joints, including fiber-end separation, fiber-end angle and Fresnel reflection. Specific details and precautions in minimizing splice process loss will be covered in following sections of this application note.

Splicing Practices

The key parameters related to attaining a high-quality single fiber fusion splice are as follows:

Work Site Preparation

Careful site preparation is essential to produce a reliable fusion splice. Adverse environmental conditions such as dust, precipitation, high wind and corrosive atmospheres should be controlled to avoid problems with fiber alignment and contamination. Once the fiber is stripped, cleaved and cleaned, speed is essential to minimize contamination-related problems. Contamination on the bare fiber surface during the arc-fusion step may increase splice loss, reduce splice tensile strength, or both.

Cable Preparation

Cable preparation and handling procedures for a particular cable design normally are recommended by the specific cable manufacturer and should be followed carefully. However, some general fiber-related precautions apply for all cable designs. Sufficient individual fiber lengths should be available such that when each spliced fiber pair is completed, the slack fiber will mount properly into the organizer without sharp bends or kinks. Also, some excess fiber length may be required should an unacceptable splice need to be remade.

Fiber Preparation

Fiber Stripping:

The fiber coating can be removed by several techniques, most commonly using a mechanical stripping tool, but thermal stripping equipment or chemical stripping also exists. For typical acrylate-coated fibers, mechanical stripping is recommended because it is fast, safe, inexpensive and creates a well-defined coating termination. Visual on mechanical stripping can be seen in Figure 3 below.

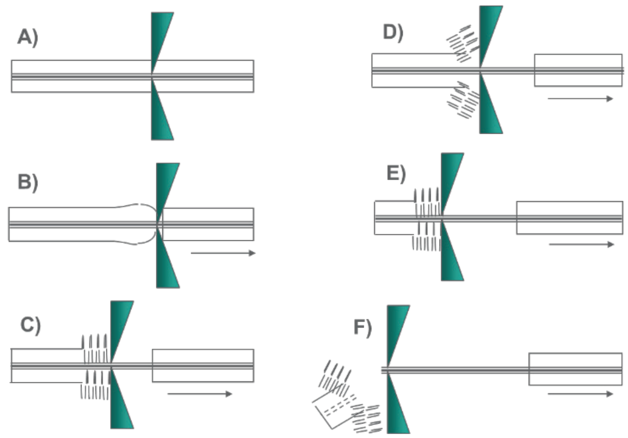


Figure 3

It is important to note that, when stripping fibers, care must be taken to avoid damaging the fiber surface. The stripping tool should be the proper size and designed for the fiber and coating combination being stripped. Also, to avoid damage to the glass surface, no more than two inches of the coating should be stripped at one time. Chemicals that soften the acrylate coatings are slower and create a poorly defined coating termination. Additionally, residual action of chemicals may cause the acrylate coating to soften and degrade long after the splice has been packaged, potentially causing splice failure. For this reason, all fibers exposed to the chemical solvent must be thoroughly cleaned after stripping.

Surface Cleaning:

Any acrylate coating residue that remains after stripping should be removed from the bare fiber surface. A clean, lint-free cotton (or alcohol-soaked) pad gently pulled over the fiber surface works well for most mechanically stripped fibers with acrylate coatings. It is important to handle bare fibers as little as possible from this point until the splice is complete. Taking this precaution will minimize the chance of contaminating the fibers with dust or body oils, which may contribute to higher splice losses and lower tensile strengths. It is also important to complete the remaining splicing process as quickly as possible, since delays will expose the fiber to additional airborne contaminants. Failure to utilize careful cleaning practices may cause the glass surface to become abraded leading to lower splice strength.

Fiber-end Angle:

Since the primary attribute affecting single fusion splicing is the end angle, proper fiber-end preparation is a fundamental step in obtaining an acceptable fusion splice. Fiber-end angle requirements vary slightly from user to user, depending on the splice loss requirements and the cleavers used. However, in general, end angles less than two degrees yield acceptable field fusion splices (typical end angles with well-controlled cleavers are around one-half degree).

Fiber Alignment

For either manual or automated alignment, it is important to ensure that the V-grooves of the equipment are kept clean and debris is routinely wiped or blown off between splices.

Manual:

The initial alignment step for single fiber fusion splicing is to mount the clean, cleaved fibers into the alignment blocks and/or holding mechanism of the splicer. First, visually align the fibers in the lateral (X-Y) directions. Visual alignment requires maintaining the smallest gap possible between the fibers, thus reducing the visual errors that may occur when manually aligning the edges of the fibers under magnification.

Automatic:

For fully automated fusion splicing units, initial alignment involves nothing more than placing the fibers in the V-groove chucks. The unit will automatically align the fibers.

Alignment Methods:

Once the fibers have been prepared for fusion (stripped, cleaved, cleaned appropriately and placed in the splicing machine), several equipment alternatives and methods of fiber core alignment exist:

1) Power monitoring using a source and detector;
2) Use of Optical Time Domain Reflectometer (OTDR) power monitoring;
3) Local injection and detection techniques;
4) Profile alignment techniques; and
5) Passive V-groove alignment.

Early Fusion Splicers

Early fusion splicers relied on external power monitoring techniques. The power monitoring technique determines optimum fiber alignment by the amount of optical power transferred through the splice point. A source, transmitting light at the system wavelength, is connected to the input end of one fiber. The transmitted light passes through the splice point and is detected by an optical power meter at the output end. Fiber alignment is achieved by moving the fibers in the X and Y lateral directions until the maximum power reading is obtained. This alignment method requires one person to monitor the output power level, and a communications link to the person operating the splicer. This method, suitable for both multimode and single-mode fibers, is an improvement over visual alignment, in that it optimally aligns the fiber cores rather than the cladding. Fibers also can be aligned using an OTDR instead of a remote power meter as in the power alignment method. OTDR alignment, however, depends on the ability of the OTDR to provide a suitable real-time display of splice alignment optimization.

Modern Fusion Splicers and Technology Advancements

Modern fusion splicers perform automated alignment through one of several techniques that is integrated into the splicer. Core alignment splicers (three-axis alignment) is ideal for fusing single-mode fiber because it provides precise fiber core alignment. Active V-groove splicers have an “active”/ movable V-groove. This provides a more precise fiber alignment than a “fixed” v-groove splicer. Accuracy of these splicing machines are well suited for single-mode fibers and FTTx applications. Clad alignment splicers, which are commonly used for ribbon splicing, have a fixed-grove, single-axis alignment. Internal cameras and a fixed-groove aid in the alignment of the fibers.

Another alternative is to use a Local Injection and Detection (LID) System, which is found on many fusion splicers. Essentially, the LID is a power-alignment system self-contained at the fusion site. LIDs eliminate the need for remote monitoring; the fibers on either side of the splice point are bent around cylindrical mandrels small enough to allow the injection of light through the fiber coating on the input side, and detection on the output side.

Profile alignment systems are often used in the splicing realm. Collimated light is directed through the fibers at right angles to the fiber axis, at the splice point itself, producing an image of the fiber that can be brought into alignment. Some profile alignment units create a computer-generated image of the core centerlines, which the computer automatically brings into alignment prior to fusing. As discussed prior, other active profile alignment units perform the alignment using the fiber clad profile. Here, the quality of alignment depends on the core/clad concentricity. With passive fixed V-groove alignment techniques, the fiber alignment is a result of precision machined V-grooves and precisely controlled fiber clad diameter and core/clad concentricity.

Fusing

Once the fibers are optimally aligned, the fusion process can be initiated. However, prior to pre-fusion, one or more short bursts of arc current often are used to remove any contaminants from the fiber ends. This step is generally included in the normal fusion cycle.

The next step in the fusion process is called pre-fusion. During the pre-fusion step, the fiber ends are heated to soften the joining fiber ends. This assures that the fiber ends are at optimum temperature during the subsequent fusion step, thus allowing the fibers to flow (melt) together upon physical contact. Too high a pre-fusion temperature causes excessive fiber-end deformation and may change the glass geometry, resulting in a poor-quality splice. On the other hand, too low a pre-fusion temperature may cause mechanical deformation of the fiber ends and subsequent fiber buckling as the fiber ends are forced together during the fusion step.

The optimum fiber temperature profiles are affected by both the pre-fusion and final fusion arc parameters (arc current and time) as well as the time period the fiber ends remain separated before physical contact. While the methods of pre-fusion vary from splicer to splicer, they can be grouped into two main categories: gradual or burst preheating. The method of pre-fusion determines the uniformity of heat distribution on the fiber-end surface. A gradual or stepped pre-fusion (Figure 4) achieves a uniform heating of the whole fiber end surface, whereas the burst pre-fusion (Figure 5) concentrates the heat on the very outer edge of the fiber ends causing a chamfering effect.

Illustration of the Heating Effect on the Fiber End Face Due to a Gradual Pre-fusion Cycle
Figure 4

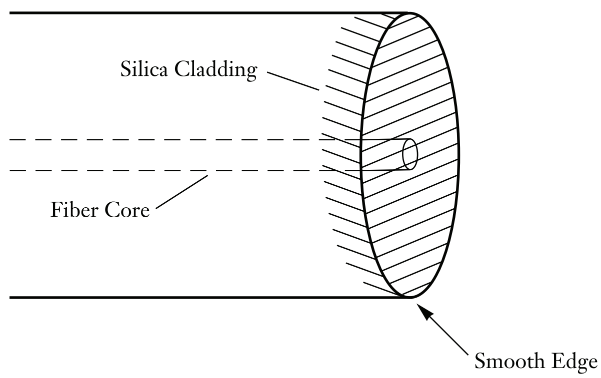
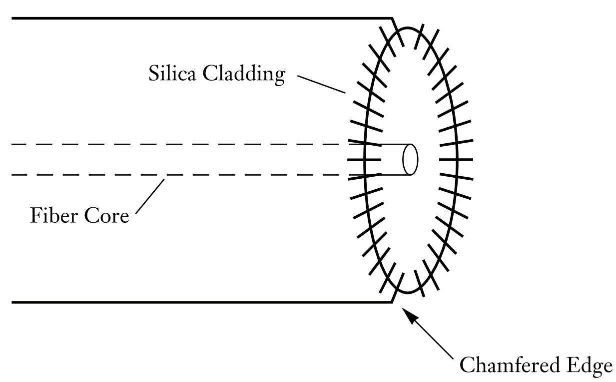


Illustration of the Heating Effect on the Fiber End Due to a Burst Pre-fusion Cycle
Figure 5



Although both pre-fusion techniques (burst and gradual) provide for high quality splices, they potentially can affect the visual appearance of the splice joint. This difference in visual appearance is discussed later in this note.

Optimum splicer settings for pre-fusion, arc current, arc time, gap and overlap (stuffing) depend on the type of splicer, the fiber type and manufacturer (composition). In addition, the prevailing environmental conditions such as temperature, humidity and barometric pressure (altitude) also may affect the optimum settings.

Modern Fusion splicers are routinely provided with pre-set programs intended to optimize splicing of particular fiber types. Some optimization of splicer settings in the pre-set programs (e.g. adjustment of the settings for pre-fusion/fusion arc current and duration, gap distance, and overlap, etc.) may be required on a job-by-job basis to achieve satisfactory performance. Bellcore has validated the need for splicer setting changes in Technical Reference TR-NWT-000020 Issue 5 Section 2.5: "... when fusion splicing fiber from different suppliers the slightly different chemical compositions (and melt temperatures) of the fibers may require that the settings of the splicing machine be adjusted."

Splice Evaluation

As mentioned in the section "Factors Affecting Splice Quality" (pg. 2), two main parameters define the quality of the fusion splice: fiber strength and induced loss at the splice point. Many splicers incorporate a pre-programmed pull test after the fiber is fused. If the fiber doesn't break, it passes the test. Another practice is to determine the characteristic tensile strength of spliced fibers using specific equipment and techniques to assure consistent splice practices in the field.

Induced loss generally is checked by remote OTDR or power meter in a fashion similar to that described for alignment. If the loss is unacceptable, the fiber should be re-spliced. Accurate measurement of splice loss (both intrinsic and extrinsic) by the OTDR requires averaged bidirectional measurements.

A common practice of splicing operators is to use a visual inspection to evaluate splice quality. For example, bubble splices, kinks, bulges, neck-downs, and dark lines at the splice joint have been associated with high-loss, low-strength fusion splices.

It is important to note that the visual appearance of any splice is dependent on the angle of view, the lighting, and the optics used when visually evaluating a splice joint.

Fusion splicing of standard Si-Ge core fiber (e.g., Corning® SMF-28® Ultra) generally results in a clear pristine splice when viewed with standard fusion splicer optics. However, under reflected light, even the most perfect fusion splice can be noticeable as a vertical line. After completing a good splice, depending on the viewing optics of the fusion splicer (typically using transmitted light), the actual splice may be visible. The visible joint results from a difference in the material index of refraction in the splice region and may be present even when a perfectly good joint is made, particularly in the case of advanced Si-core fibers such as Corning SMF-28® ULL. Lines may also be identified when splicing between fiber types of different refractive index profile design e.g. SMF to NZDSF or Si-Ge Core to Si Core or different manufacturing techniques e.g. Outside Vapor Deposition (OVD) to Inside Vapor Deposition (IVD). Figures 6 and 7 below provides an illustration of the difference between homogeneous and heterogenous fiber splices.

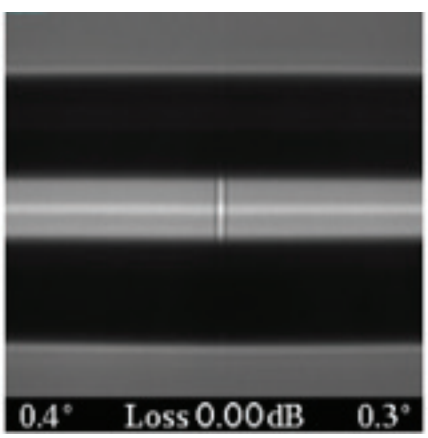


Figure 6. SMF-28® ULL to SMF-28® ULL

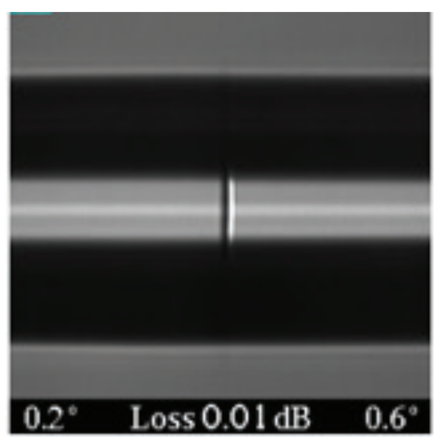


Figure 7. SMF-28® ULL to SMF-28® Ultra

Finishing Up

Once the fiber is satisfactorily spliced and properly protected (typically with a heat shrink sleeve), the completed splice assembly should be secured into the splice organizer. Routing of the fibers must be checked within the splice organizer to assure that the proper fiber bending radius is maintained, and that the fibers are not inadvertently bent over any sharp edges.

Safety Considerations

Some precautions and care must be exercised when preparing and fusing fibers. All loose fiber pieces should be controlled and properly disposed of. Fusion splicing involves a high-voltage electric arc and should not be attempted in explosive environments. Many machines have exposed electrodes that can pose shock hazards for operators. The power alignment methods, as well as LID and OTDR testing, inject laser radiation into the fiber, which can create permanent damage if the end of an active fiber is held too close to the eye. Therefore, never look closely into the end of a fiber that may be under test.

Problem Splices–Troubleshooting

Problems during splicing may occur from time to time, even under the most ideal conditions.

For instance, bubble splices usually result in high loss. They are caused by dirt or coating particles trapped and gasified in the splice, or by an improperly set fusion arc current. Careful fiber preparation, a clean splicing area, and optimum splicer settings for fiber type and environment will reduce potential contaminants and keep bubble splices to a minimum.

Kinks can occur when fibers are misaligned during splicing and can produce high losses. The cause usually is dirt in the splicing platform V-grooves, or improperly cleaned fibers with acrylate coating material incompletely removed during the stripping operation.

Bulge splices result from too much compression prior to or during splicing. A bulge usually will not seriously increase splice loss unless it is excessive and is rarely a problem with automatic splicers.

Incomplete splices can occur if fiber ends are not sufficiently parallel, or if insufficient heat is applied. Applying more heat to complete the fusion process usually creates an acceptable splice. Unless corrected, these splices are very weak mechanically, and exhibit high loss.

Necked-down splices also exhibit high loss and should be redone. They can result from insufficient fiber overlap and excessive heating of the fiber ends prior to fusion.

With current splicing technology, fibers do not break at the splice joints because the glass at the splice joint is melted together. This melting process acts to heal the surface flaws induced during fiber preparation and handling prior to splicing. Therefore, when tensile-loaded to failure, the spliced fibers routinely will break in the region adjacent to the melted splice joint. The fibers break in this area due to the presence of flaws induced during the preparation processes (such as mechanical stripping and cleaving) or aggravated by the arc heating process. In addition, the area adjacent to the splice joint is on the fringe of the fusion arc, subjecting it to thermal cycling. As with general “welding” principles, it is this adjacent region that typically weakens the most.

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