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Is That Splice Really Good Enough? Improving Fiber Optic Splice Loss Measurement

NEMI Fiber Optic Splice Improvement Project

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Abstract
Results from a National Electronics Manufacturing Initiative (NEMI) project, formed to improve aspects of fiber optic fusion splicing, are reported. The focus of this paper is ultra low loss splicing for telecommunications product assembly, with typical loss of <0.05 dB per splice for standard SMF-SMF. A detailed review and gap analysis of available industry standards, relevant to splice loss acceptance criteria and loss test procedures, revealed the standards are generally inadequate for low loss splicing. Various project participants using different equipment and procedures performed fiber preparation, splicing, splicer loss estimation, and actual loss measurements. Sets of data spanning three loss ranges, obtained with three measurement methods were compared using an industry standard gage repeatability and reproducibility (GR&R) analysis. A subsequent comparison of loss measurement set-ups based on a cut-back method for dissimilar fiber (SMF-EDF) splices showed significant directionality in some cases, and root cause was identified using a round robin approach. A future activity of this project will be to draft a new loss measurement standard for dissimilar fiber splices, to address an important gap in the current standards.

Key words: optoelectronics, optical fiber, fusion, splice, loss measurement, gage R&R

Introduction

Fusion splicing is the preferred method for optical interconnection of fiber pig-tailed components used in optoelectronics products based on the requirements for low loss, stable joints. The most important attributes of a splice are mechanical strength and optical insertion loss. Low splice loss is critical for internal product splicing since the loss budget, the maximum allowed loss for proper function of the optical circuit, is usually very stringent. For example, a loss target of <0.05 dB per splice is common. The interdependence of the factors that cause unpredictable variation in splice loss has been previously described.[1-3] These include fiber batch properties (mode field diameter, core/cladding concentricity), fiber preparation processes (cleaved end face condition, presence of contaminants) and splicer parameters (arc power and duration), which affect core diffusion and alignment during splicing, and thereby the optical transmission of the splice. For low loss splicing, measurement uncertainty can be a particular problem, and the repeatability and reproducibility (R&R) of the optical loss test system is rarely assessed but assumed to be adequate.

For product splicing of pig-tailed components, actual splice loss measurement is usually not possible since the free ends of the fiber are not accessible for connection to a source and detector. Therefore, it is necessary to rely on the loss estimate provided by the splicer. Yet, it is observed that the splicer loss estimator values often have poor correlation to the actual splice losses (Figure 1). The accuracy and distribution of the estimated loss values are critical because these determine the splice loss (pass-fail) acceptance criterion. Poor estimator accuracy requires setting the estimate acceptance value well below the loss budget, to ensure that only a small number of bad splices escape. However, this results in a low splice yield and a large fraction of splices to be reworked, as well as likely rejection of good splices.

In order to assess the accuracy of the splicer estimator loss values a capable measurement system is required, which typically implies an R&R value of ±10% of the range, or ±0.005 dB for low loss splicing applications. Although variation in insertion loss from optical components, polarization effects or movement of the fiber may exceed this value, to compare different measurement methods and user set-ups it is necessary to measure to the precision limit of the test equipment.

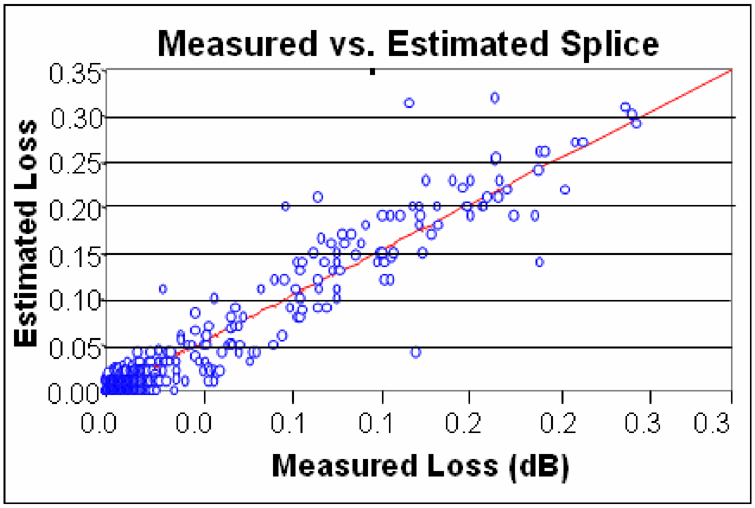

Figure 1 - Correlation of the Splicer Estimator and Measured Loss (Typical Values Shown)

The practical aspects of how to achieve repeatable measurements for low-loss similar and dissimilar fiber splices were the main drivers for forming a National Electronics Manufacturing Initiative (NEMI) member project in mid-2002. The objectives of the project are to assess the repeatability of different measurement methods and set-ups, and to incorporate the best practices in draft standards for adoption by the appropriate industry organizations. Use of common test methods will enable comparison of loss test and splicing equipment between vendors and users, and potentially lead to improvement in the accuracy of loss estimators and better splice yield for low loss applications.

The initial tasks of the project were selected by surveying the members for topics that ranked highly in terms of potential benefit, likelihood of success and members' enthusiasm. A secondary factor surveyed was whether the topic had been previously investigated, either by a member company or reported in the literature. The highest ranked activities were: (1) a review and gap analysis of available standards relevant to splicing, (2) an objective assessment of the various low splice loss measurement methods and setups used by the members, (3) to quantify the accuracy of splicer loss estimators, and (4) to assess splice loss test methods for dissimilar fiber types, such as SMF to erbium doped fiber (EDF). Results on topics (1), (2) and (4) are reported in this paper.

Standards Review

The first major activity of the project was to perform a comprehensive review and gap analysis of industry standards relating to fusion splicer and splice acceptance, splice test, reliability, and environmental test requirements. The initial effort focused on reviewing the standards readily accessible to the members, and this was extended as further standards were obtained.[1-14] Because of space limitations, only the standards most relevant to splice loss acceptance and yield, as well as insertion loss test methods and equipment are discussed here. It should also be made clear that while we attempted to be thorough in our compilation and review of the standards, the project members did not have access to copies of all potentially relevant standards, including the full range of IEC standards.[15-17] The standards are not clear whether a splice should be considered a fiber or a passive component, and because classification as a pig-tailed component or device may sometimes be more appropriate, relevant fiber standards were also reviewed.

Splicer and Splice Loss Acceptance Standards

The reviews of standards relating to fusion splicing and splice optical loss are summarized in Appendix A. The most relevant were Telcordia standards GR-765, for Single Fiber SMF Splices and Splicing Systems and GR-1095 for Multi-Fiber SMF Splices and Splicing Systems, and British Telecom's standard BT-LN-469E. Each addresses many features desired or required in fusion splicers with some attention to splice loss performance, loss estimation, and test/verification methods. The term "passive" splicing used in Telcordia GR-1095 refers to mini, micro or ribbon splicers utilizing "cladding" (more appropriately referred to as fixed V-groove) alignment or viscous centering, as opposed to "active" splicing used by full feature core alignment splicers using either image processing or LID (light injection and detection) to actively align the two fibers in 3 axes to optimize their coupling. (This is somewhat confusing since the term "active splicing" is also widely used to describe achieving a desired splice loss value using feedback to the splicer from an external source and power meter to optimize the power coupling between the two fibers.) A potential conflict between the splice mean loss and loss yield requirements and objectives criteria in GR-765 is discussed in the initial list report (ILR).[18] For example, a set of 20 splices could have 19 low loss splices and a single high loss splice, and meet the yield requirement of 95% of splices ≤0.10 dB, but fail the mean loss ≤0.10 dB requirement. Telcordia also states that the splice loss estimator accuracy requirement (and objective) in GR-1095 specify limits for 90% and 100% of the population, which is practical, but conflicts with the criteria in GR-765, which applies to all splices of the set.

We found several important gaps across the standards reviewed to date:

- Current standards do not cover dissimilar fiber splicing, such as SMF to EDF. There is an urgent need to address this.
- Newer fiber types, such as 80 µm diameter, NZ-DS, LEAF, etc, are not mentioned. This is not surprising since some standards are more than six years old.
- Most of the standards concentrate on outside plant or field splicing for optical network applications and do not address controlled factory applications, as for module assembly.
- Insufficient attention is given to fiber preparation processes, which are critically important to achieve low loss and high splice yield. Default guidelines should be provided.
- Splice loss test procedures (source stability, measurement accuracy and repeatability, etc.) are generally inadequate for low loss product splicing, with typical loss requirement of <0.05 dB per splice.
- Reporting requirements should include the fiber preparation acceptance criteria and fusion splicer settings

Splice Loss Test Standards

Standards relating to splice loss measurement methods and test equipment are summarized in Appendix B. Again, we identified a number of important gaps:

- TIA 455-34A, the most widely recognized and comprehensive standard, does not mention the geometry error or nominal tolerances for test fibers, e.g. core concentricity, which is specified in Telcordia GR-765. Neither standard addresses other important fiber properties such as mode field diameter (MFD), core effective index and backscatter coefficient. This information may not be necessary for the in-line methods, in which a single fiber is cut and spliced. However, in the cutback or bare fiber adapter (BFA) methods, in which the two fibers are likely to be dissimilar, intrinsic characteristics of the fibers, such as absorption, may need to be considered.
- Measurement accuracy is specified in some standards. For example Telcordia GR-326 (single mode optical connectors and jumper assemblies) calls for accuracy within ±0.05 dB (section 5.2), and Telcordia TR-001196 (splice verification sets) requires ±0.2 dB and an objective of ±0.1 dB (section 4.1.1), for losses between 0.0 and 1.0 dB.[4,6] However, the standards do not describe how to assess method accuracy. There is a need for traceable standard components (fiber splices or attenuators) in the low loss range of 0-0.05 dB, to avoid extrapolation and assumptions of linearity from the higher attenuation ranges covered by commercial instruments.
- A source stability of <0.01 dB (Telcordia) is barely adequate for low loss splicing in the range 0-0.05 dB, where measurement repeatability of 10% of the range requires stability of ±0.005 dB, or better. The best current data (in-line sets I-1 & I-2, see Results and Discussion section) demonstrate that short-term stability of ±0.001 dB is achievable. However, the TIA 455-34A (section 3.1.3) target of ±0.02 dB is inadequate. At the same time, TIA provides for more precise low loss measurement by including a source monitor to control source drift.
- The TIA specification for detector resolution of 0.01 dB, for losses <0.5 dB, is also inadequate for low loss measurement.
- Useful information on test set-ups, such as coupling the fiber to the detector (e.g. integrating sphere), use of fiber loops as high order mode filters, and isolators to prevent back reflections, is generally omitted. TIA 455-34A (sections 4.3 & 4.4) has the best coverage and mentions that for SMF the fiber coating is often sufficient to function as a cladding mode stripper, fiber lengths can be as short as 2 m, and there should be no bends with radii <3 inch within the test fibers.

Both the in-line and BFA methods are covered in TIA 455-34A, although TIA refers to "cutback method" or "pigtailed devices" when describing the loss tests described in this paper as BFA. Of the various standards reviewed, TIA 455-34A comes closest toward satisfying the need for a precision loss measurement method, and with some modification and addition, it could be adopted as a new standard for very low loss splicing.

Experimental Methodology

To quantify the capability of current splice test methods, several optical test systems were assessed in relation to various loss ranges, fiber and splice types. The measurement stability and repeatability were used to quantify each system's performance and make comparisons.

Source Stability Test Method

To assess the stability of optical power for each measurement system, a series of tests was conducted to monitor the drift of optical power over time. During these tests, each system was referenced and allowed to drift for a period equal to the time required to complete a set of fusion splices and loss measurements. For each measurement system, three runs were conducted with thirty data points acquired evenly over the evaluation period. The maximum deviation from the reference, across all three runs, was used as the metric for source stability.

Gage R&R Test Method

To assess the repeatability of each test system, a gage repeatability and reproducibility (GR&R) study was conducted. This investigation required the production of 10 splices for a given process range. Each splice was measured three times, using one to three operators in a random order, resulting in three to nine measurements per splice. These repeated measurements also captured the variation resulting from fiber handing. Between each measurement, the operator moved the fiber to simulate handling that would normally occur during splicing. This data was then used to determine the measurement R&R by calculating the 99% spread of this distribution, taking into account both the equipment and appraiser variation represented by each data set.[18]

One of two methods was then used to calculate the measurement variation as a percentage of process based parameters. The "range" based GR&R procedure determines the commonly quoted percent R&R by calculating it as a fraction of the total variation.

$$\% R \& R = 100 * \frac{R \& R}{TV} \qquad (1)$$

$$R \& R = \sqrt{EV^2 + AV^2} \qquad (2)$$

$$TV = \sqrt{R \& R^2 + PV^2} \qquad (3)$$

Where R&R = Repeatability and Reproducibility
EV = Equipment Variation
AV = Appraiser Variation
PV = Parts or Process Variation
TV = Total Variation

Alternatively, the total variation in (1) can be replaced with the defined process range or tolerance under investigation (Equation 4). This was done to consistently calculate the repeatability of several independent data sets as a fraction of the range under investigation.

$$\% R \& R = 100 \frac{R \& R}{Tolerance} \qquad (4)$$

In either method, the measurement system should ideally provide a percent R&R value of ≤10% for acceptable discrimination, 10-30% for marginal and >30% GR&R for poor.[18]

The errors associated with stability and repeatability were combined using a root sum of squares approach that assumes the variables are independent.

Measurement Systems Evaluation Overview

Techniques commonly used to measure splice loss include an optical power source and meter, or an optical time domain reflectometer (OTDR). There are many variations possible when using a power source and meter, but in general they fall into one of two categories. With the in-line method, the fiber ends remain fixed throughout the entire testing process. In the BFA or "cutback" method, the fiber directed to the meter is reconnected for every measurement and splice. These methods begin with setting up a reference fiber, then measuring the splice loss compared to the reference. For standard SMF fibers, the fiber under test has negligible intrinsic loss over a few meters length. If the fiber has significant loss, compensation for the fiber loss must be included.

The test methods were also divided between those that accommodate similar and dissimilar fibers. For the purposes of this paper, similar fibers are defined as those fibers that are essentially identical by design, e.g. from the same fiber part number. Dissimilar fibers are defined as those fibers that differ by design in optical and/or materials properties, such as refractive index profiles. Dissimilar fibers typically have different mode field diameters (MFD). The MFD describes the fiber's beam intensity distribution and mismatches can result in significant contribution to the splice loss, according to Equation 5.[19,20]

$$MFD_{Loss}[dB] = -10\log\left[\frac{4}{\left(\frac{MFD_1}{MFD_2}+\frac{MFD_2}{MFD_1}\right)^2}\right] \qquad (5)$$

In-line Method for Similar Fiber Splices
The initial setup consisted of a reference fiber between an optical source and a power meter. The system was allowed to stabilize, the meter's wavelength was matched to the source and the meter was referenced. Then the fiber was cut and spliced back together, with the new power meter reading representing the splice loss.[21] A schematic of the in-line test method is shown in Figure 2.

There are several setup variations that may make the in-line method more repeatable and robust. These include the use of cladding mode strippers (per TIA 455-34A), use of external isolators, securing fibers to prevent unnecessary movements and the use of an integrating sphere in conjunction with a BFA at the detector. Ideally, a BFA and an integrating sphere will remove any measurement dependence on how the fiber is attached to the detector. See Figure 2 for some possible setup variations.

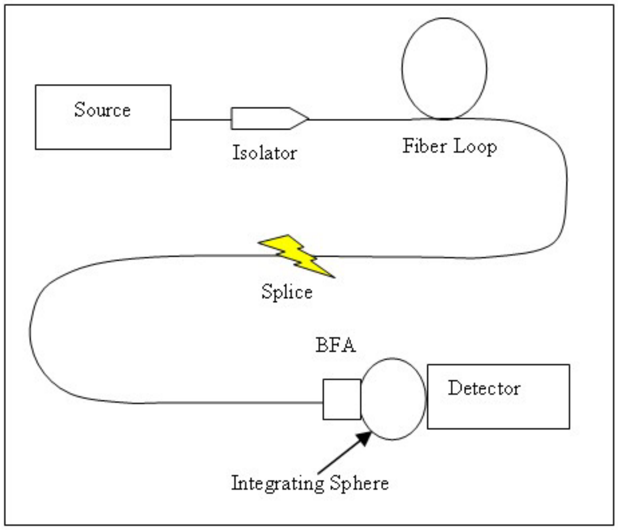

Figure 2 - In-Line Method for Similar Fibers

Bare Fiber Adapter Method for Similar and Dissimilar Fibers
Due to the changing fiber end face, it is preferred to have a BFA receptacle or integrating sphere on the detector to minimize the variability of the connection. As with the in-line method, the BFA method began by waiting for the source to stabilize and matching the source and detector wavelength settings. The fiber end directed to the power meter was prepared and inserted into the BFA. The BFA was then inserted into the detector or integrating sphere and the power meter was referenced (see Figure 3, first stage). Next, the fiber was removed from the BFA. A piece of test fiber was cut, prepared at one end and inserted into the BFA. The other end of the test fiber was spliced to the reference fiber. The new reading on the meter indicates the splice loss (or the combined splice and fiber losses if the test fiber has non-negligible loss). A second length of test fiber may be added to enable measurement in the other direction, as shown in the third stage of Figure 3.

Repeat measurements on a single splice were made by removing the test fiber from the BFA, re-preparing the end and reinserting the fiber. Further splice samples were made by cutting out the test fiber, re-zeroing the reference fiber, and inserting a new test fiber between the reference fiber and the BFA. Many of the same setup variations can be made for the BFA method as for the in-line method.

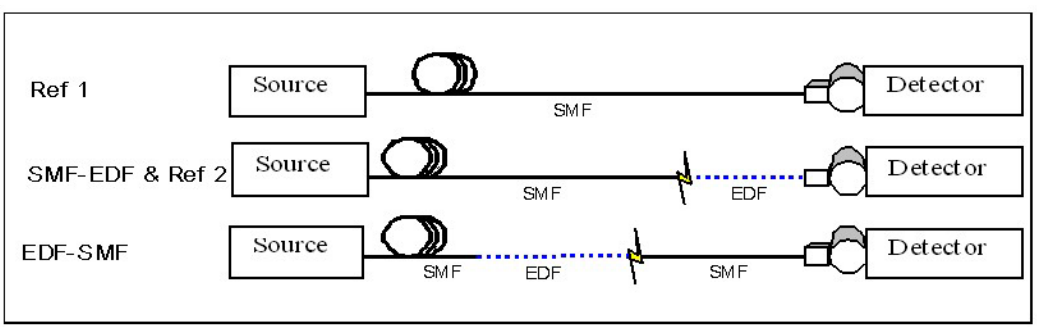

Figure 3 - BFA Method Setup for Measuring Dissimilar Fibers in Two Directions

It should be noted that the BFA method can be used to evaluate the splice loss for both similar and dissimilar fibers combinations. For similar fibers the reference fiber and test fiber would be virtually identical. For dissimilar fibers, either fiber could be the "reference" or "test" fiber. However, if the test fiber exhibits significant intrinsic loss, a calculation to correct for this effect is required.

Optical Time Domain Reflectometer Method (Similar Fibers)
The OTDR launches a powerful pulse of light into a fiber and then monitors the light backscattered along the fiber. By constructing a chart of received signal versus time, and converting "time" to distance by knowing the speed of light in the fiber (c/n), the OTDR creates a chart of all measurable attenuation effects in the fiber, such as splices and connectors, versus their distance from the meter.[22] The use of an OTDR for fusion splice and splicer evaluation is described in Telcordia GR-765-CORE and particularly detailed in TIA/EIA fiber optic test procedures (FOTP) 455-8 and 455-59.[13,14]

The general OTDR test setup is shown in Figure 4. The meter was connected to a 2.2 km reel of SMF fiber through a short connectorized jumper. The test splices were made between this reel and a second 2.2 km reel of SMF fiber certified identical by the manufacturer. Care was taken to select OTDR settings, particularly pulse width (long) and averaging time (at least 30 seconds), to optimize its loss calculation accuracy. The 4-point linear slope analysis (LSA) method was used automatically by the OTDR for loss calculation of "non-reflective" events, i.e. splices.

It should be noted that the stability assessment method was not used to evaluate the OTDR due to the nature of the method. Since the OTDR is continuously self-referencing, all backscattered readings are relative to each launch pulse. The stability of the optical source over a period longer than the pulse return time is therefore irrelevant.

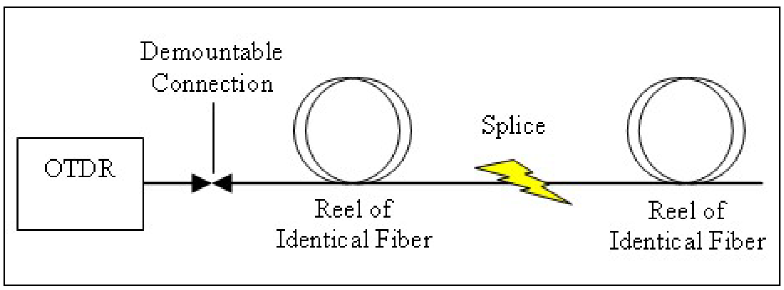

Figure 4 - Schematic diagram of OTDR Test Setup for Splice Loss Measurement

Similar Fiber Test Method Comparison
Test setups representing the In-line, BFA and OTDR methods were compared using the stability and repeatability metrics previously discussed. Each test method was typically assessed across three process ranges representing various splice losses. The process ranges under investigation were 0–0.05 dB, 0.05–0.15 dB and 0.15–0.30 dB. In order to obtain data points that fully span each process range (i.e. "lossy" splices), changes to the splice time and splice power, as well as intentional attenuation splices, were made as required.

Dissimilar Fiber Test Methods Comparison
The purpose of investigating the loss measurement of dissimilar fiber splices was to evaluate the performance of different user test setups and to determine whether splice losses are significantly different depending on the direction in which they are measured. Our gap analysis showed that dissimilar fiber splicing needs to be addressed in any proposed standard method.

To encompass variation in the BFA test based on Figure 3, measurements were made amongst four different user set-ups, all operating at 1310 nm wavelength. Similar to previous evaluations, measurement repeatability was assessed by GR&R. A limitation of the Figure 3 method is that different splices are required to make measurements in each direction.

In order to determine whether dissimilar fibers exhibit directional loss properties, a procedure was developed to allow the same spliced section to be measured in both directions (see Appendix C). This procedure enables a paired comparison of the directional splice losses, whereby several of the measurement variables are common to each direction. For the purpose of this paper, the more unusual fiber or the fiber that may absorb (e.g. EDF) will be referred to as Fiber A, and the more common or non-attenuating fiber (e.g. standard SMF) will be referred to as Fiber B.

Referring to Appendix C, first a dissimilar fiber splice sample was made using approximately one meter of each fiber type. Then, the BFA test method was configured with a standard single mode launch fiber. Fiber A of the sample was then spliced to the launch fiber to set-up what will be referred to as the "forward" direction (e.g. EDF→SMF). The Fiber B end of the sample was then mated to the detector using the BFA and the system was referenced. A measurement of the Fiber A length (L1) was made and the sample was cut in the Fiber A section close to the launch fiber connection. The portion of fiber that remained attached to the launch fiber was then mated to the detector using the BFA and the resulting gain (G1) was measured. The remaining length of Fiber A (L2) was measured and the splice loss was calculated using Equation 6.

$$\text{Loss }(A \rightarrow B) = G1 - (L1-L2)(\text{Absorption}_{\text{Fiber A}}) \qquad (6)$$

Fiber B of the sample was then spliced to the launch fiber, to make the "reverse" direction (e.g. SMF→EDF). Fiber A of the sample was then mated to the detector using the BFA and the system was referenced. A measurement of the Fiber A length (L4) was made and the sample was cut in the Fiber B section close to the launch fiber connection. The portion of fiber that remained attached to the launch fiber was then coupled to the BFA and detector, and the resulting gain (G2) was measured. The splice loss was calculated using Equation 7.

$$\text{Loss }(B \rightarrow A) = G2 - (L4)(\text{Absorption}_{\text{Fiber A}}) \qquad (7)$$

In order to efficiently and thoroughly address the two issues outlined at the start of this section a round-robin investigation was designed, as shown in Table 1.

Table 1 - Round-Robin Experiment Design ("f" Denotes Forward Direction & "r" the Reverse)

Test Setup		A EDF1 to SMF1	B EDF1 to SMF2	C EDF1 to SMF3	D EDF2 to SMF4
B-1	BFA with Int. Sphere	3 x 5 f 3 x 5 r	"	"	"
B-2	BFA with Int. Sphere	"	"	"	"
B-3	BFA only	"	"	"	"
B-4	BFA only	"	"	"	"

The round-robin experiment consisted of four fiber combinations (A-D), with five splice of each. Three combinations were spliced by different users with the same EDF (type 1) and different standard SMFs (15 splices). The last combination consisted of a different EDF (type 2) and was prepared by only one user (D), giving an additional 5 splices. The four BFA test setups (B-1 to B-4), which encompassed the test system variation, primarily differed in that only two used an integrating sphere. The five samples for each fiber combination were measured in both directions using the Appendix C method for each test setup. Three repeat measurements were made for each splice section and each direction, to assess repeatability for the gage R&R assessment.

Far Field Intensity Distribution Method

In an effort to better understand the directionality that can sometime be observed when measuring the losses of dissimilar fiber splices, a far-field intensity distribution of the fibers involved in this study was performed. The far field scanning system used for these experiments consisted of a light source (a 1310 nm laser diode pigtailed with SMF-28 fiber), a power meter with remote detector head, and a computer for control and data acquisition (Figure 5). To ensure that a stable mode field distribution was established, a minimum of 1 m of the fiber under test was spliced into the source. The detector head was fitted with an opaque disk, with a small pinhole in the center allowing only a small portion of the sensing element to be exposed to the light emitted from the fiber under test. This modified detector head was mounted on a precision, motor controlled arm (approximately 150 mm long) that could be swept in an arc about the cleaved output end of the fiber under test. The received power as a function of sweep angle was recorded for sweep angles of approximately ±20º from the center peak power position.

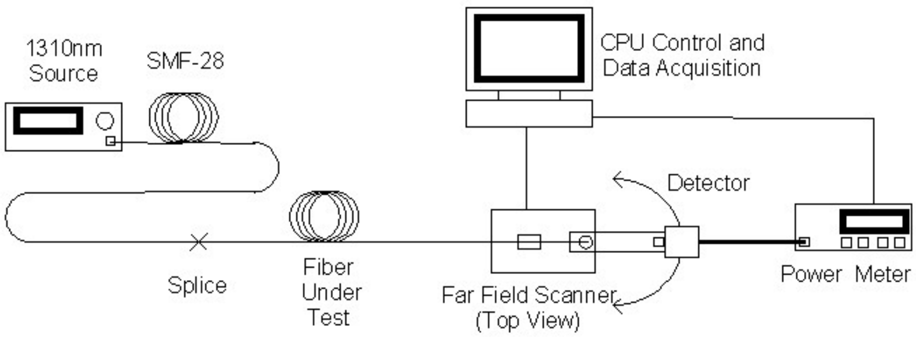

Figure 5 - Schematic of the Far Field Scanning System

Results and Discussion

Measurement System Stability

The results shown in Figure 6 and Table 2 summarize the stability data for each test system. Four groups used the in-line method (I-n), four the BFA method (B-n), and one used the OTDR method (O-1). Maximum drift values were found to vary from 0.0028 to 0.0472 dB across test systems. While the repeatability of these values will depend on the magnitude and range of losses being measured, even the largest range under investigation would be significantly affected by the worst case stability, as it accounts for 30% of the process range. Although the key factors influencing stability are not discussed in this paper, the results emphasize the need for verification of test methods, even when using standard industry equipment in relatively simple applications.

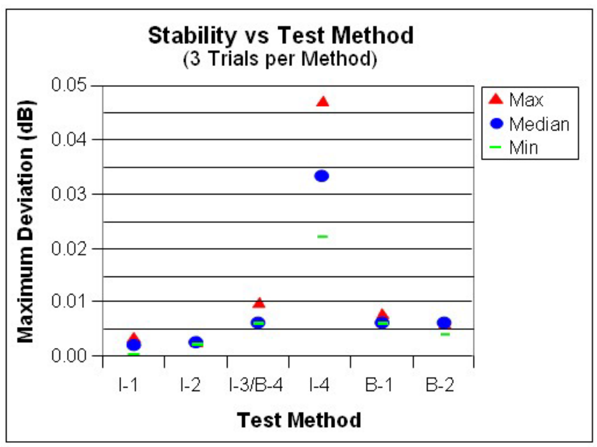

Figure 6 - Stability of the different test methods

Table 2 - Stability Test Data (Two-Sided Values Shown)

	I-1	**I-2**	**I-3 / B-4**	**I-4**	**B-1**	**B-2**
Max Drift (dB)	0.0034	0.0028	0.0100	0.0472	0.0080	0.0060
Median Drift (dB)	0.0020	0.0026	0.0060	0.0332	0.0060	0.0060
Min Drift (dB)	0.0004	0.0020	0.0060	0.0222	0.0060	0.0040
Max/Low Range (%)	6.8	5.6	20.0	94.4	16.0	12.0
Max/Mid Range (%)	3.4	2.8	10.0	47.2	8.0	6.0
Max/High Range (%)	2.3	1.9	6.7	31.5	5.3	4.0

Gage R&R for Similar Fiber Splices

The data in Figure 7 and Table 3 provide a summary of the variation due to measurement repeatability and stability across the lowest range investigated (0-0.05 dB), a range frequently encountered during the manufacture of optical assemblies. Considering only the % R&R data, it is interesting to note that only 5 of the 9 methods were able to meet the 10% threshold and obtain a rating of "adequate". The addition of the stability results further degraded the performance with only two of the methods now meeting the 10% threshold.

It is also interesting to note that significant levels of variation could be found both across and within each test method. For example, even within the in-line test method, results varied by a factor of three or more. The percentage of repeatability and reproducibility over the total process variation ranged from 2.4% to 16.1%. Similar results are shown for the BFA method. Group B-3 obtained a very high value, which is indicative of a faulty gage.

The results of the study indicate that many of the commonly used methods for assessing optical power loss need careful implementation and assessment to achieve trustworthy and meaningful results. Also, the data did not suggest that any one method (in-line, BFA, OTDR) was consistently superior. Possibly, factors such as splice and test equipment, testing environment, and whether or not an isolator is used, play a bigger role than anticipated. These findings further emphasize the need for standards that describe the practical aspects of low loss splice testing in more detail. The level of detail of the methods in the standards reviewed is insufficient to achieve acceptable R&R for low loss measurement.

Table 3 - Gage R&R Test Results (Two-Sided Values) – "I" Refers to In-Line, "B" the BFA and "O" the OTDR Methods

Setup-User	R&R (dB)	% R&R (%)	Stability (dB)	% R&R + Stability (%)
I-1	0.0012	2.4	0.0034	7.2
I-2	0.0026	5.3	0.0028	7.7
I-3	0.0054	10.9	0.0100	22.8
I-4	0.0080	16.1	0.0472	95.8
B-1	0.0154	30.7	0.008	34.6
B-2	0.0036	7.2	0.006	14.0
B-3	0.0769	153.8	---	---
B-4	0.0052	10.3	0.010	22.5
O-1	0.0190	38.1	---	38.1

Note: stability assessment was not made for method B-3 and was not required for the OTDR method

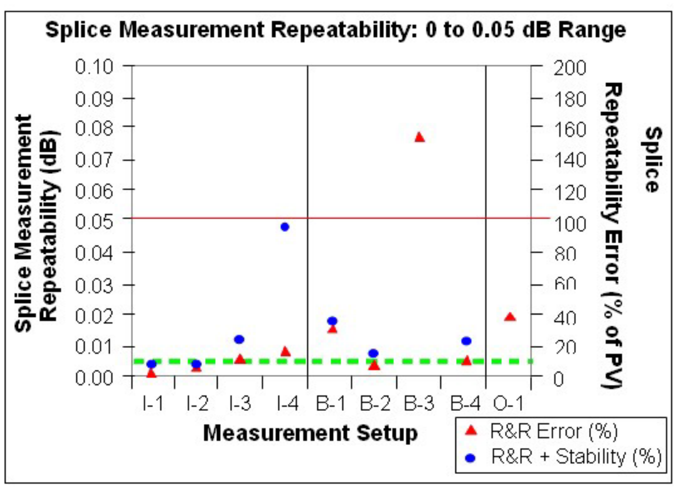

Figure 7 - Splice Measurement Repeatability over the Low Loss Range for All Test Methods for Similar Fiber Splices

Dissimilar Fiber Splices
Splices made with dissimilar fiber combinations are commonly used in OE modules, e.g. optical amplifiers typically contain several standard SMF to EDF splices, and achieving the required loss budget is critical to the performance of the module. As discussed above, the currently available splice loss standards do not address dissimilar splice loss testing. Suppliers, OEMs and assemblers generally use their preferred (often different) method, which makes comparison and verification of fiber and product-level measured splice loss values problematic. Hence, there is a need to verify the methods in use, compare repeatability, identify any issues and submit best practice methods as candidates for standards.

Gage R&R Results
Users' implementation of the two BFA-cutback methods, different splices and same splice in each direction (see Figure 3 and Appendix C, respectively) were assessed using gage R&R. The values shown in Table 4, based on a typical loss process range (tolerance) of 0.2 dB for SMF-EDF, indicate both methods have acceptable measurement repeatability. The contribution to the variation from stability (not shown in Table 4), would approximately double the R&R values (cf. Table 3).

Table 4 - Gage R&R results for SMF-EDF splice loss measurement at 1310 nm (Two-Sided) - EDF Type 1 was Used unless Indicated and Values for Each Direction are Combined

Test Method	Test Setup	Max GR&R (%)	Min GR&R (%)	Avg. GR&R (%)
Appendix C	B-1	8.8	7.8	8.3
Appendix C	B-3	4.5	3.0	3.7
Figure 3	B-4	1.5	0.9	1.2
Appendix C	B-4	1.6	1.5	1.6
Appendix C	B-5	3.0	1.5	2.2
App. C (EDF-2)	B-5	3.0	0.0	1.5
Appendix C	B-6	4.6	3.4	4.0

Effect of Measurement Direction and Other Variables
The BFA-cutback method has the advantage of enabling the splice loss to be measured in the forward and reverse directions for dissimilar fibers, e.g. when the fibers have mismatched MFDs, as for SMF-EDF splices. Theory predicts there should be no directionality dependence for pure Gaussian mode propagation (as can be verified by interchanging the subscripts in Equation 5). Although directional dependence of the loss is not expected, to our knowledge this has not been experimentally verified. Since a proposed standard method would need to accommodate any directional dependence, this issue was addressed in the methods.

Other variables of interest include wavelength (1310 or 1550 nm), use of fiber loops as high order mode strippers, source stability and use of an integrating sphere to couple the light from the BFA into the detector (see Figure 3). Since EDF exhibits optical non-linearity and loss measurement instability in the gain region at 1550 nm, 1310 nm was used to obtain more precise measurements. Results obtained with the various set-ups based on the two BFA-cutback methods are shown in Figure 8. The divergence of the data sets indicates that some users observed significant measurement directionality, well above the measurement standard deviation.

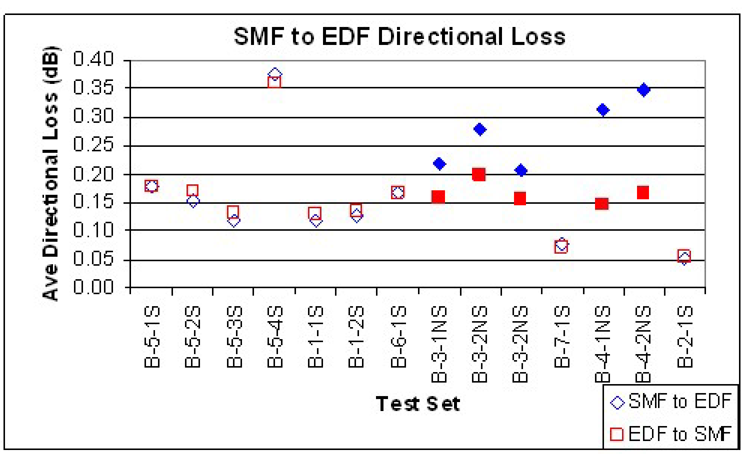

Figure 8 - Loss Data for SMF-EDF Splices, Measured in Each Direction at 1310 nm (Using BFA Methods of Figure 3 and Appendix C). Set-Ups B-3 and B-4 without an Integrating Sphere (NS) are Shown as Solid Symbols

Although the source of the directionality may be the fiber combination, the splice and/or the test set-up, a clue was revealed by ranking the data by the difference in loss for each direction, showing complete separation between set-ups that utilized an integrating sphere and those that did not (see Table 5). One user made measurements with and without fiber loops and did not observe any significant difference in directionality. Since the directionality finding was unexpected it was decided to further investigate the cause by means of a round-robin study, whereby splices made by several users are all measured on the various set-ups.

The round-robin was performed with four users, all of whom made measurements in each direction on sets of SMF-EDF splices prepared with two types of EDF (see Experimental section). The directional results (Figure 9) show that test users B-3 and B-4 obtained high directionality (>±0.05 dB). There is no significant directionality dependence associated with the fiber type, the splice preparation or the splice sample. This leads to the conclusion that the measurement set-up is the source of the directionality, and the effect correlates with absence of the integrating sphere.

Owing to the directionality measured by some of the users, a comparison of the loss values measured in the round-robin is best compared by combining the two directional values for each splice, as shown in Figure 10. The good agreement (within 0.05 dB) between different users, further supports that the observance of directionality is a measurement artifact, and not a true physical loss difference. The good agreement of average losses across measurement set-ups also points to the possibility of standardizing on a "bi-directional average" method for specifying dissimilar fiber splice loss, as an alternative to using an integrating sphere.

Table 5 - SMF-EDF Splice Loss Data Ranked by Directionality (EDF→SMF Minus SMF→EDF) Showing Dependence on Use of the Integrating Sphere ("S" with and "NS" without) Round-Robin Study

Sample Set	Integ. Sphere	Qty	SMF-EDF		EDF-SMF		Directionality (dB)
			Ave (dB)	StDev (dB)	Ave (dB)	StDev (dB)	
B-5-2S	Y	11	0.1519	0.0546	0.1691	0.0187	0.0172
B-5-3S	Y	10	0.1192	0.0281	0.1313	0.0226	0.0122
B-1-1S	Y	10	0.1186	0.0232	0.1298	0.0233	0.0112
B-1-2S	Y	10	0.1268	0.0250	0.1341	0.0253	0.0073
B-2-1S	Y	10	0.0508	0.0074	0.0545	0.0088	0.0037
B-6-1S	Y	10	0.1659	0.0470	0.1659	0.0425	0.0000
B-5-1S	Y	10	0.1786	0.0131	0.1783	0.0169	-0.0003
B-7-1S	Y	6	0.0788	0.0114	0.0732	0.0108	-0.0057
B-5-4S	Y	9	0.3778	0.0444	0.3600	0.0194	-0.0178
B-3-3NS	N	15	0.2080	0.0430	0.1560	0.0327	-0.0520
B-3-1NS	N	10	0.2193	0.0517	0.1590	0.0330	-0.0603
B-3-2NS	N	30	0.2790	0.0220	0.1983	0.0280	-0.0807
B-4-1NS	N	10	0.3142	0.0438	0.1454	0.0198	-0.1689
B-4-2NS	N	10	0.3478	0.0196	0.1655	0.0162	-0.1823

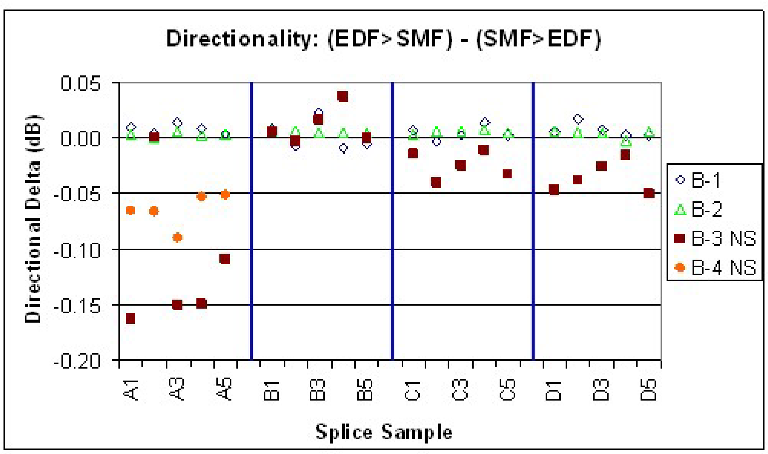

Figure 9 - Round-Robin Directional Data for SMF-EDF Splices, at 1310 nm (Using BFA Methods of Appendix C) - A-D are Fiber Combinations and B-1 to B-4 are User Test Setups (See Table 1).

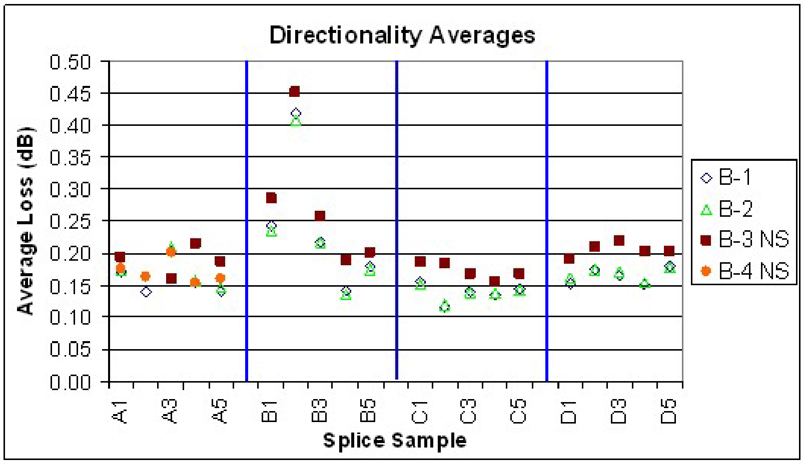

Figure 10 - Round-Robin for SMF-EDF Splices, Values for Each Direction are Combined and Averaged

Far Field Intensity Distribution Measurement

The results of the far field intensity measurements for both erbium doped fibers used in this study, as well as standard SMF, are given in Figure 11. It can be observed that both of the EDF fibers have a significantly broader far field pattern compared to standard SMF. This is as expected, given that the MFD of the erbium fibers at 1310 nm is 5.0 µm, versus 9.2 µm for SMF. (The more tightly guided the mode within the fiber, the greater the expansion exiting the fiber.) (See Ref. 23 for a detailed treatment.)

The differences in the far field patterns between EDF and SMF point to an explanation for the observance of directional splice losses with non-integrating sphere measurement systems. The purpose of the integrating sphere is to collect a constant fraction of the light emitted from the end of the fiber, regardless of angular input to the sphere (and other optical properties), and couple this to the detector. If an integrating sphere is not used, it is possible that some of the power radiating at large angles from the end of the fiber is "lost", either because it simply "missed" the detector, or because the detector has reduced sensitivity to off-axis light. Because splice loss measurements involve the detection of very small change in power, even very subtle differences in collection efficiency between fiber types can significantly influence the measurement results.

If the data of Figure 11 is plotted on a log scale, as shown in Figure 12, it is especially apparent that at high angles of incidence, significant power differences exist between EDF and SMF. If a detector system were unable to collect power at high output angles, say >12º, the reference power reading exiting EDF would be lower than actual. If SMF is then spliced on to the EDF, and a reference power reading exiting the SMF is then taken, the "lost" power from the EDF reference would now be collected, and the apparent loss of the splice would therefore be lower than actual. This was indeed the case for the non-integrating sphere measurement systems used in this study. The apparent loss was lower when splicing EDF into SMF. This also explains why the "bi-directional average" splice losses were in good agreement between all measurement systems, even when high directionality was observed (Figure 10). This is because any power that is "lost" when measuring in one direction, is identically "gained" when measuring in the other. When averaged, this adds nothing to the actual loss.

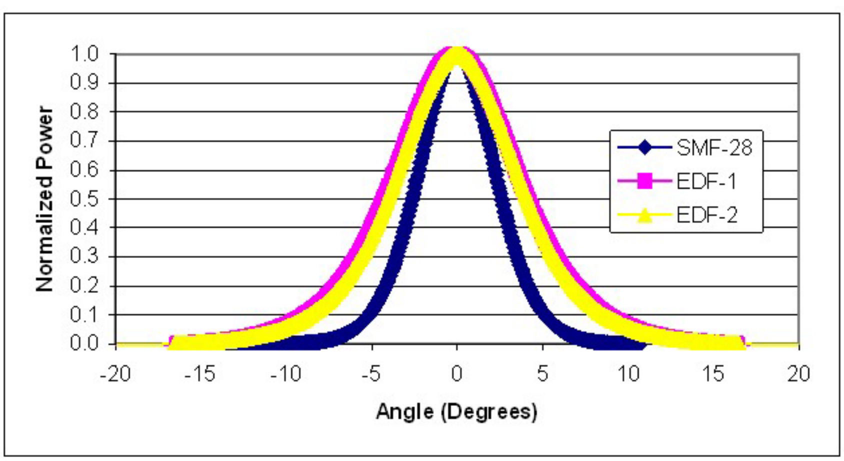

Figure 11 - Normalized Power Over ±20º (Linear Scale)

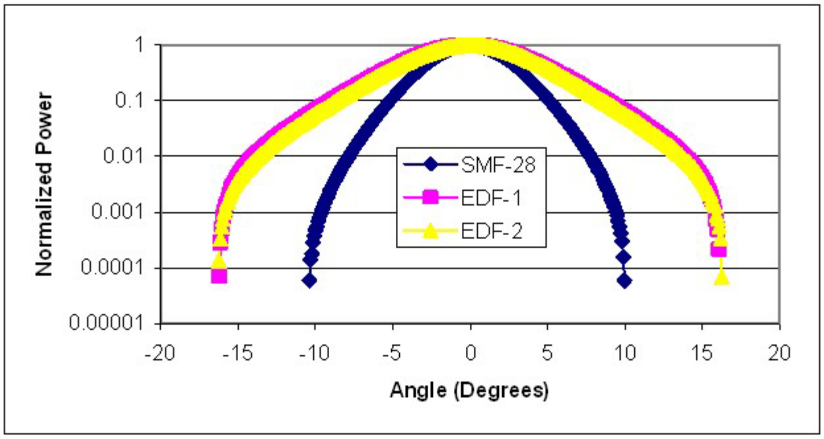

Figure 12 - Normalized Power Over ±20º (Log Scale)

Conclusions and Future Activities

A review of currently available standards related to optical fiber splicing and splice loss measurements revealed that they do not adequately address the very low splice loss specifications and dissimilar fiber splicing requirements of today's typical OE manufacturing applications. An industry-wide gage R&R study confirmed that many of the commonly used methods for measuring optical power loss need careful implementation and assessment to achieve trustworthy and meaningful results. These findings emphasize the need for standards that describe the practical aspects of low loss splice testing in more detail. The gage R&R analysis was found to be a useful way of qualifying and comparing these measurement methods and is recommended as a means for verifying measurement capability.

A round-robin measurement comparison of EDF-SMF fiber splices showed that the directionality that can be often observed in these measurements is primarily a measurement artifact and not a true directional loss difference. The use of an integrating sphere, and/or a bi-directional average splice loss method is required for accurate results.

It is recommended that the results and conclusions of this study be used or the basis of an industry-wide specification for qualifying optical splice loss measurement systems and specifying optical splice loss requirements.

Future planned activities of this project will be to verify additional test methods for dissimilar fiber splices made with various low loss fiber types, including LEAF and high NA, and to identify any additional existing standards to complete the review. The description of the loss test methods for both absorbing and non-absorbing dissimilar fiber splices will form the basis of the draft specification to be developed in collaboration with interested standards organizations.

Acknowledgements

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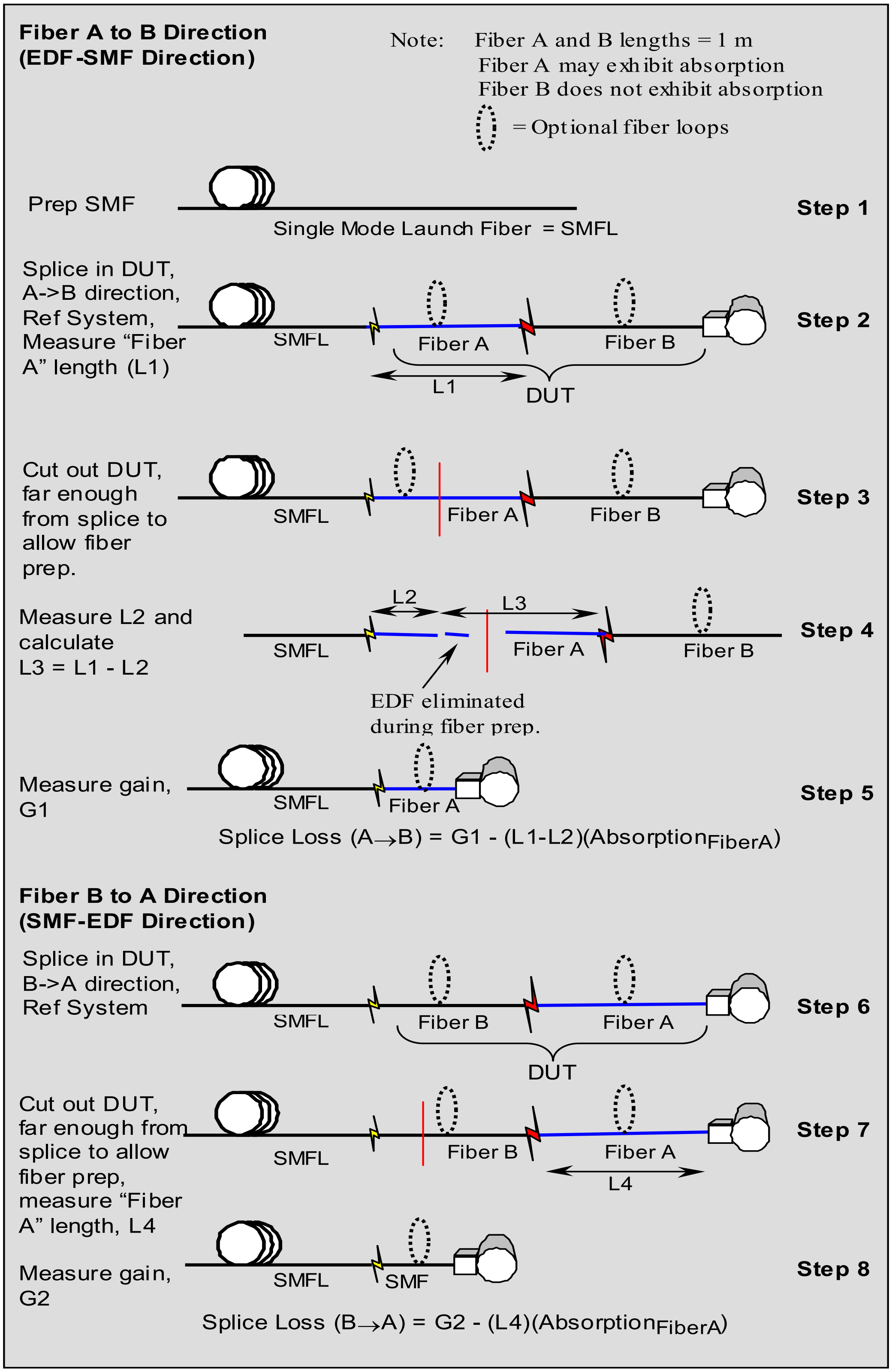
Appendix A - Key Standards Requirements Relating to Fusion Splicer and Splice Acceptance

	GR-765 Single Fiber SMF Splices and Splicing Systems	**GR-1095** Multi-Fiber SM Splices and Splicing Systems	**BT LN 469E** Machines Jointing for Single Fiber Fusion Splicers
Test fiber	≤ 0.4 μm core eccentricity. TIA fiber classes IVa & Ivb	Nominal geometry error, diameter 125±0.3 μm, core-cladding concentricity ≤0.4 μm	>0.4 μm core eccentricity. Fiber per CW 1505 and CW 1504
Mean splice loss (R = required, O = objective)	R4-85 ≤0.10 dB for fiber with nominal geometry error	R4-104, R4-110 (module) ≤0.15 dB (passive ribbon splicing)	Mean not specified
	O4-86 ≤0.05 dB	O4-105 ≤0.10 dB (passive splicing) O4-111 (within module) Std. dev. ≤0.1 dB per joint	3.1 (O) Losses follow Weibull distrbn. (shape param 1.6 & characteristic value ≈ 0.05 dB)
Splice loss yield	R4-89 95% of splices, ≤0.10 dB	R4-107 95% of joints have loss ≤0.20 dB	3.1 (R) 95% ≤0.10 dB and 99.8% ≤0.15 dB (implies data set n>500)
	O4-90 95% of splices ≤0.05 dB	O4-108 95% of joints have loss ≤ 0.10 dB R4-109 (within module) 100% <0.40 dB	
Loss estimator accuracy (CR = condition for requirement)	CR4-55 Within ±0.10 dB for actual loss ≤0.40 dB. Within ±25% for actual loss >0.40 dB (n=10 splices). NB implies 100% of est. losses	CR4-62 For actual loss ≤ 0.40 dB, 90% of estimates within ±0.10 dB of actual loss, 100% within ±0.25 dB. For actual loss >0.40 dB, 90% of estimates within ±25% of actual loss, 100% within ±50%.	3.16 ±0.10 dB on fiber with known core offset ≥0.4 μm, with random orientation Mean difference between est. and actual losses ≤ 0.02 dB (n=100 splices)
(CO = condition for objective)	CO4-56 Within ±0.05 dB for actual loss ≤0.40 dB Within ±15% for actual loss >0.40 dB	CO4-64 For actual loss ≤0.40 dB, 90% of estimates within 0.05 dB of actual, 100% within 0.10 dB. For actual loss >0.40 dB, 90% of estimates within 15% of actual loss, 100% within 30%.	

Appendix B - Standards Specifications for Insertion Loss Test Methods and Equipment

	GR-765 Single Fiber Single-Mode Optical Splices and Splicing Systems	**GR-1095** Multi-Fiber Single-Mode Optical Splices and Splicing Systems	**GR-198** Optical Loss Test Sets	**TIA 455-34A** Interconnection Device Insertion Loss Test	**TIA 455-8 and 59** Measurement of splice or connector loss and reflection using an OTDR
Splice insertion loss test method (attenuation, transmittance)	5.1.4.1 In-line with selectable (optical switch) reference fibers, also OTDR per TIA 455-59.	5.1.4.1.1 In-line, measure continuous fiber, then break, splice and re-measure. Optical switch to select test or ref fibers. Also OTDR method.	Optical loss test sets (OLTS) used for outside plant optical network. Hand-held types with integrated optical source & power meter	1.1, 1.3, 5.1 & 5.2 SM splicing (test method B), procedures. In-line version and cut-back equivalent to "BFA". Recommends source monitoring.	OTDR , single fiber
Source wavelengths and spectral width	1310 and 1550 nm	5.1.4.1.4 1310 ± 20nm and 1550 ± 20nm spectral width ≤ 75 nm	R4-1 Dual λ capability. At 1310 nm: LED ≤140 nm, laser ≤5 nm. At 1550 nm: LED ≤150 nm, laser ≤5 nm	3.1.1 660, 850, 1310 & 1550 nm. Center wavelength ±30 nm, spectral width <140 nm for 1310 nm (LED or laser diode)	850, 1300, and 1550, ± 20 nm
Source stability	5.1.4.1.4 <0.01 dB over measurement period	5.1.4.1.4 <0.01dB over period required to make one set of measurements	R4-2 Within ±0.5 dBm over 8 hr period at (23±2°C)	3.1.3 "Greater" of ±0.02 dB over period of test or 10% of max attenuation	Not specified
Accuracy	Not specified	Not specified	R4-17 ≤±0.5 dBm at Pin –10 dBm Optionally –25dBm	Not specified	Calibrated to ≤ 0.05 dB
Detector range, response power (RP) and linearity	5.1.4.1.4 ≥60 dB below source power Linearity not specified	5.1.4.1.4 ≥60dB below the source power Linearity not specified	R 4-11 Min RP –55 dBm Max RP +1 dBm Linearity not specified	3.4 Must measure all power emitted from output fiber. Linearity within 5% of range of power	None specified
Resolution	Not specified	Not specified	Not specified	3.6.2 Better than 0.01 dB for loss <0.5dB	Min. reportable loss of non-reflective "event" (splice) ≤0.10 dB

Appendix C - Splice Loss Directionality Procedure



NEMI National Electronics Manufacturing Initiative, Inc.

Is That Splice Really Good Enough?

Improving Fiber Optic Splice Loss Measurement

Presented on Behalf of the Project Members

by Peter Arrowsmith

02-26-2004

Optoelectronics TIG

Fiber Optic Splice Improvement Project

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Improved Fiber Splicing Project

- Project Objective (from Statement of Work):
  - To develop and promote industry-wide test methods and splice quality criteria that will allow for systematic investigation of variability, comparison of equipment, improved yield and lower costs

- Project Benefits:
  - Promote the use of common metrics and measurement methods
  - Identify the sources of loss measurement variation for future improvement
  - Submit methods and guidelines for incorporation into OE standards, e.g. IPC-STD-0040

- Meeting Objectives:
  - Share technical results
  - Promote awareness of project activities
  - Attract companies to participate in follow-on OE projects

Areas of Interest & Priorities

- Surveyed members to rank possible activities by expected benefit, likelihood of success and level of enthusiasm
- Survey included a wide range of topics relevant to the assembly of spliced optical modules
- Top Ranked Areas of Interest:
  - Review existing standards (Telcordia, TIA, IEC, IPC, etc)
  - Test method(s) for insertion loss (IL) of dissimilar splices (SMF-EDF, etc)
  - Splice acceptance metrics (measured & estimated IL, strength)
  - Estimated IL accuracy: compare methods, splicer vs measured, identify which loss mechanisms are included, potential improvement
  - Test method for strength (strain rates)
  - Test method for extinction ratio for PM fiber (fiber stressing for worst case vs non-stressed for repeatability, etc)
  - Splice reliability

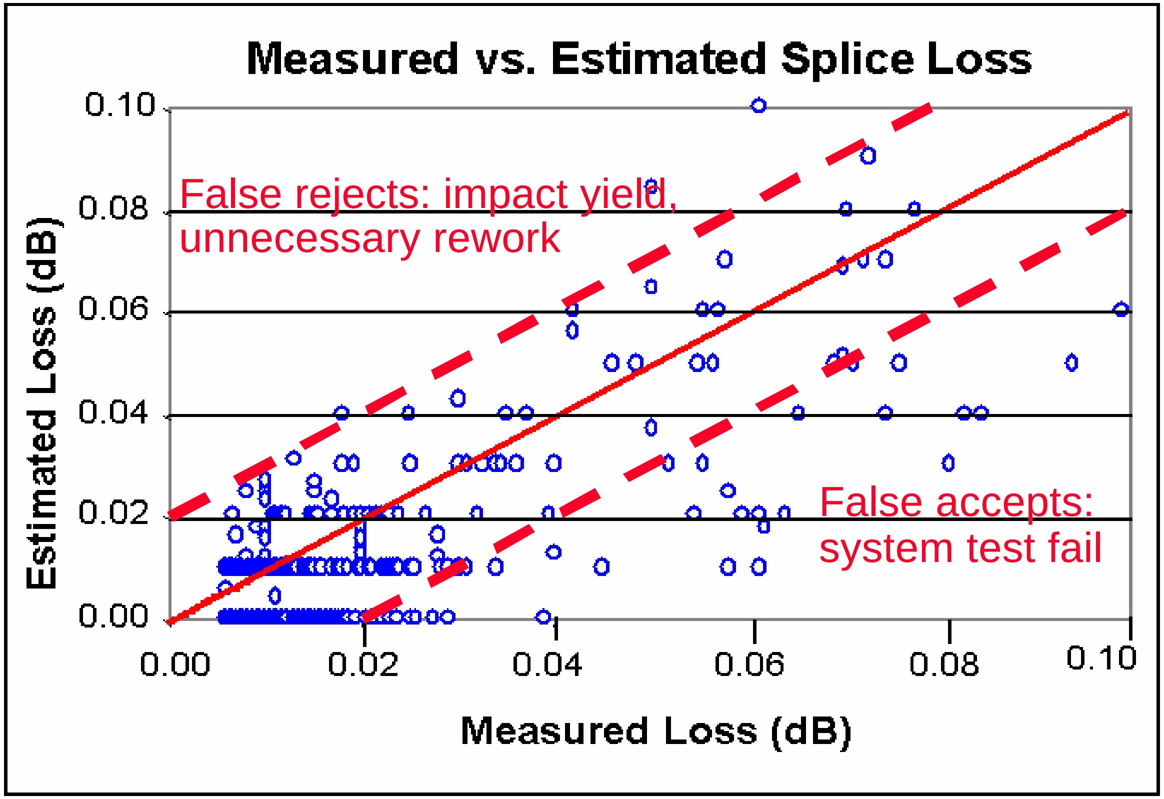
Drivers: Why Loss Test Measurement?

- Different groups (fiber & equipment suppliers, OEMs, EMSs, Test Development, Manufacturing) often use different test methods
- Methods include: BFA, cut-back, add-on, inserted section, OTDR
- Test variables: measurement direction (e.g. SMF to EDF), 1310 vs. 1550 nm, use of fiber loops, integrating sphere, source stability, etc.
- Unknown measurement capability (R&R) and accuracy, poor correlation between measured and splicer estimated values
- Makes comparison of specs difficult for fiber batch, estimated values, splice & optical module loss budget requirements
- There are no standards for dissimilar fiber splice loss measurement
- Current standards do not address ultra low loss splices for optical module assembly (~0.05 dB/splice loss budget for some applications)
- It is necessary to assess measurement capability at the limit of the test system, ideally ≤10% of the smallest value to be measured

Correlation of Measured vs. Estimated Loss

- **Measured vs Estimated Loss**
  - **Low loss splicing for module assembly requires more accurate loss estimation**
  - **Active splicing is used to ensure accuracy, but requires optical I/O access**
  - **What are the failure modes for the outliers?**
  - **Can the estimation be improved (software/hardware)?**

Figure shows Measured vs Estimated insertion loss for SMF-SMF splices on different 'PAS' style splicers



Connect

Current Status of Project and Synopsis

1. Standards review. Request to IEC to distribute IEC 61073-3/1073-3 to group	80% complete
2. SMF-SMF gage R&R comparison of member's splice loss test methods	Complete
3. Correlation of estimated vs. measured loss	80% complete
4. Loss estimator accuracy metrics, confidence limits	50% complete
5. Statistical comparison of actual loss distributions based on 1000 splice data sets,	50% complete
6. SMF-EDF splice loss repeatability, BFA method	Complete
7. SMF-EDF splice round robin (directionality)	Complete
8. Standards organization collaboration	In-progress
9. Verify loss test methods for dissimilar fiber splices	In-progress
10. Draft splice loss standard	Planned

1. Standards Review

Goals

- Improve knowledge of existing specifications from Standards bodies
- Review all relevant specifications to see if product-level splicing requirements are addressed, vs. field/network splicing
- Compare standards to identify gaps, conflicts and overlaps

Actions Taken

- Identified the following bodies:
  - ITU-T, ETSI, JSA, Telcordia, TIA/EIA, IEC, BT, IPC & DOD Mil Stds
- Members split up workload and concurrently reviewed standards on-hand
- The following standards bodies have most relevant specifications:
  - Telcordia (TRs, GRs…), TIA (FOTPs…), IEC
- Approached IPC-PMA, Telcordia, TIA and IEC representatives to request additional standards, copies for use within project, and to develop partnerships
- TIA and IPC are enthusiastic to work with NEMI project on improved or new splice standards

Note: Project members would like to thank TIA for providing CD copies of the TIA standards requested.

Standards Review: Splicer & Splice Acceptance

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	O4-86 ≤0.05 dB	O4-105 ≤0.10 dB (passive splicing) O4-111 (within module) Std. dev. ≤0.1 dB per joint	3.1 (O) Losses follow Weibull distrbn. (shape param 1.6 & characteristic value ≈ 0.05 dB)
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	O4-90 95% of splices ≤0.05 dB	O4-108 95% of joints have loss ≤ 0.10 dB R4-109 (within module) 100% <0.40 dB	
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Standards Review: Splice Loss Test

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Splice insertion loss test method (attenuation, transmittance)	5.1.4.1 In-line with selectable (optical switch) reference fibers, also OTDR per TIA 455-59.	5.1.4.1.1 In-line, measure continuous fiber, then break, splice and re-measure. Optical switch to select test or ref fibers. Also OTDR method.	Optical loss test sets (OLTS) used for outside plant optical network. Hand-held types with integrated optical source & power meter	1.1, 1.3, 5.1 & 5.2 SM splicing (test method B), procedures. In-line version and cut-back equivalent to "BFA". Recommends source monitoring.	OTDR , single fiber
Source wavelengths and spectral width	1310 and 1550 nm	5.1.4.1.4 1310 ± 20nm and 1550 ± 20nm spectral width ≤ 75 nm	R4-1 Dual λ capability. At 1310 nm: LED ≤140 nm, laser ≤5 nm. At 1550 nm: LED ≤150 nm, laser ≤5 nm	3.1.1 660, 850, 1310 & 1550 nm. Center wavelength ±30 nm, spectral width <140 nm for 1310 nm (LED or laser diode)	850, 1300, and 1550, ± 20 nm
Source stability	5.1.4.1.4 <0.01 dB over measurement period	5.1.4.1.4 <0.01dB over period required to make one set of measurements	R4-2 Within ±0.5 dBm over 8 hr period at (23±2°C)	3.1.3 "Greater" of ±0.02 dB over period of test or 10% of max attenuation	Not specified
Accuracy	Not specified	Not specified	R4-17 ≤±0.5 dBm at Pin –10 dBm Optionally –25dBm	Not specified	Calibrated to ≤ 0.05 dB
Detector range, response power (RP) and linearity	5.1.4.1.4 ≥60 dB below source power Linearity not specified	5.1.4.1.4 ≥60dB below the source power Linearity not specified	R 4-11 Min RP –55 dBm Max RP +1 dBm Linearity not specified	3.4 Must measure all power emitted from output fiber. Linearity within 5% of range of power	None specified
Resolution	Not specified	Not specified	Not specified	3.6.2 Better than 0.01 dB for loss <0.5dB	Min. reportable loss of non-reflective "event" (splice) ≤0.10 dB

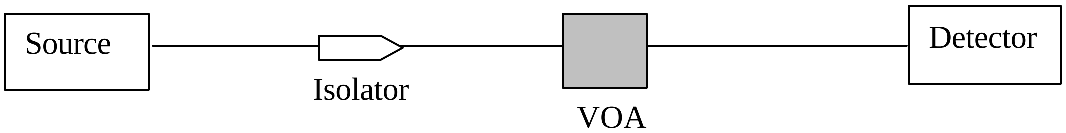
Table 2. Standards Specifications for Insertion Loss Test Methods and Equipment

Standards Review – Key Findings

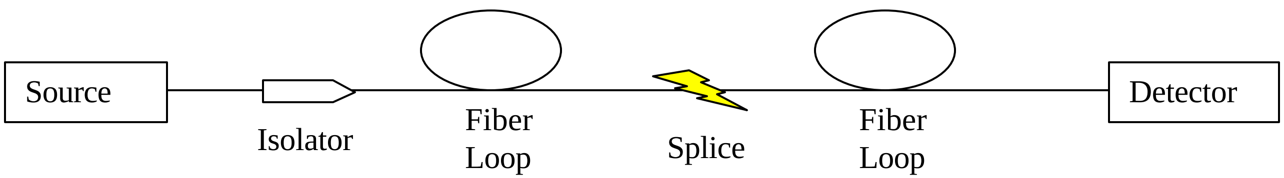
- Many of the standards that cover splicing are 6 or more years old and therefore do not cover newer fibers (80 μm, NZ-DS, LEAF) or fiber combinations such as dissimilar splicing (SMF-EDF, etc).
- For standards purposes, it is not clear whether a splice should be considered a fiber or a passive component
- Most of the standards do not address splicing for optical module assembly
- Most specs consider splice losses of 0.1-0.4 dB to be acceptable
- Splice loss test requirements (source stability, measurement accuracy and repeatability, etc) are generally inadequate for low loss product splicing
- For today's products with SMF-SMF, low loss splices of 0.0-0.05 dB are routine, requiring measurement repeatability of $\pm$0.005 dB (10% of the range)
- A source stability of <0.01 dB (Telcordia GR-765, 1095) is barely adequate
- Practical information on test set-ups and methods are generally omitted
- TIA 455-34A comes closest to meeting our needs for a loss measurement method

2. Member Splice Loss Test Methods

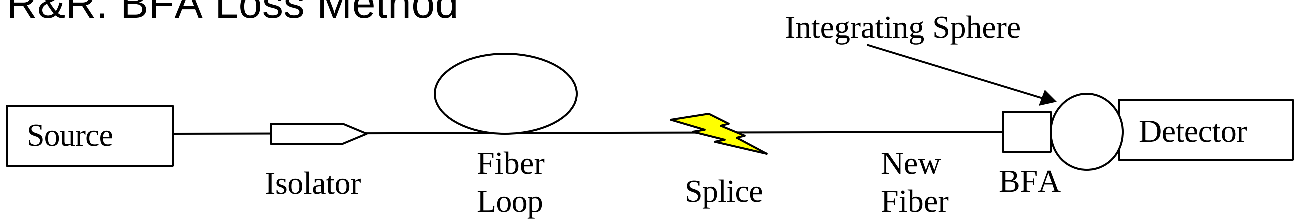
1. Stability: In-Line or BFA Methods (linearity requires VOA)



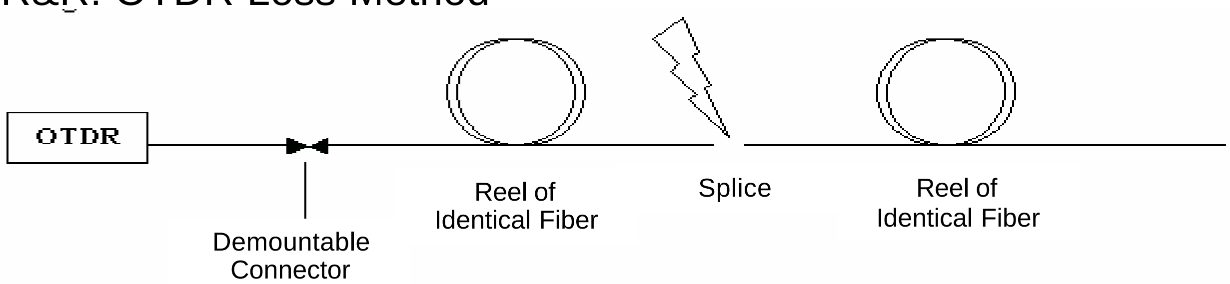
2. Gage R&R: In-Line Loss Method



3. Gage R&R: BFA Loss Method



4. Gage R&R: OTDR Loss Method

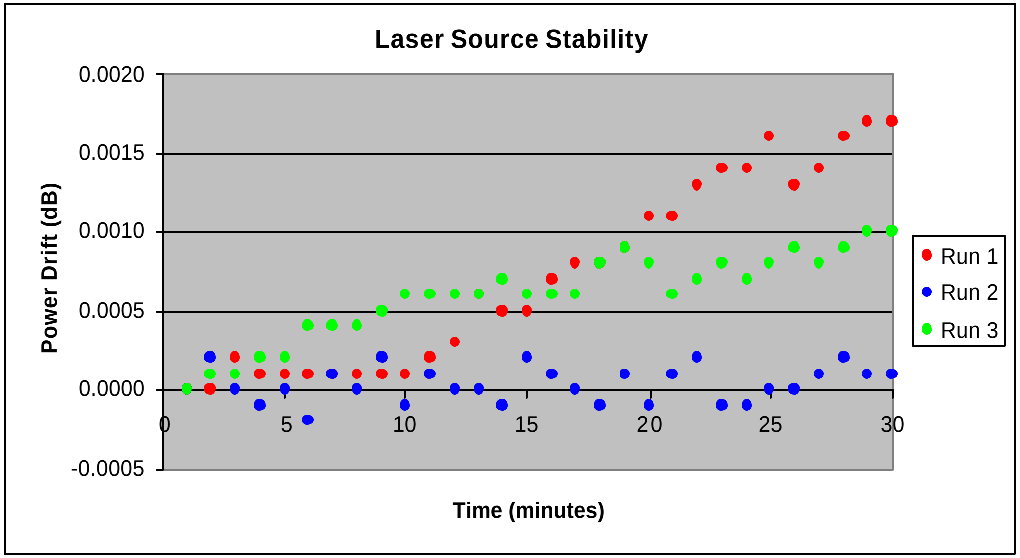


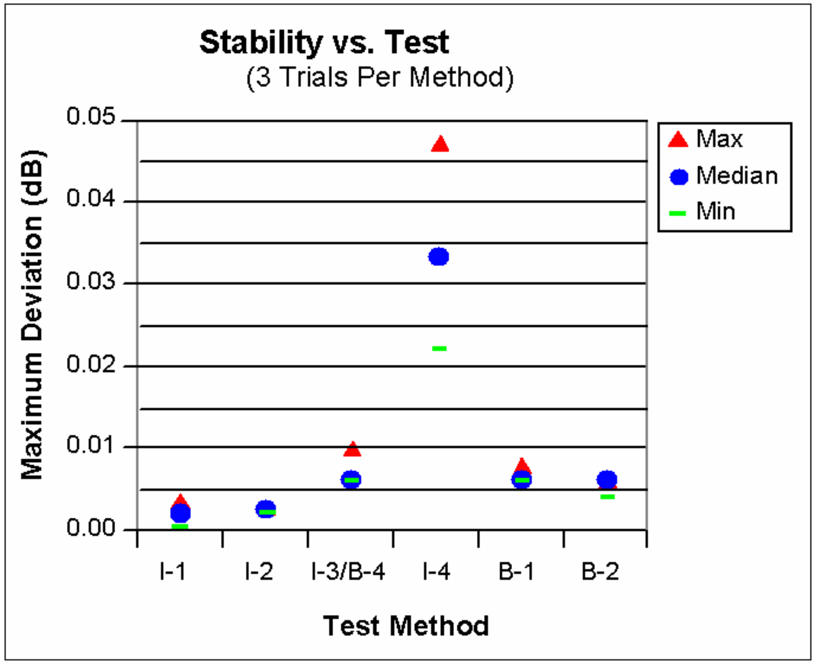
Gage R&R Test Method and Data Collection

- Members submitted Gage R&R data using the In-line, BFA and OTDR methods
- Three loss ranges (0-0.05, 0.05-0.1, 0.1-0.15 dB), each measured by up to three operators
- Splicing and test equipment varied between members. Also variations in test setup, e.g. use of isolators, mode filters (fiber loops), coupling to detector & methodology
- Measurement repeatability as a percentage of the range is acceptable (≤10%), marginal (10-30%) or unacceptable (>30%)
- All used the same Gage R&R spreadsheet calculator
- Parameters recorded and used:
  - Measured loss (assumed to be actual loss)
  - Splicer estimated loss
  - Periodic source power & detector reading for stability monitoring (except OTDR method)
- Recorded only: cleave angles, splicer condition (arc time, power), env. conditions

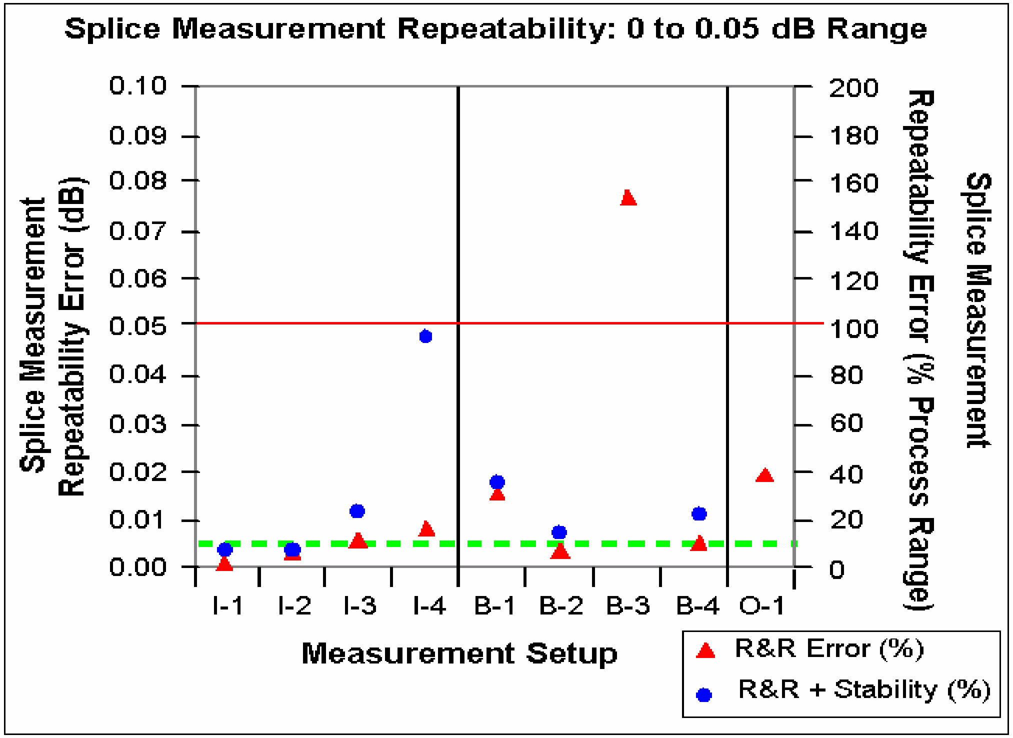
Splice Measurement Repeatability: Gage R&R Stability

- Three stability runs per measurement system (except for one BFA)
- Source stability is not relevant for OTDR (µs to ns pulse)
- Time interval over which stability was monitored was the same as the splice process & measurement period
- The maximum drift deviation of the 3 runs was used to define the stability error





Splice Measurement Repeatability
Gage R&R Study – Results



	R&R (dB)	% R&R (%)	Stability (dB)	% R&R + Stability (%)
I-1	0.0012	2.4	0.0034	7.2
1-2	0.0026	5.3	0.0028	7.7
1-3	0.0054	10.9	0.0100	22.8
1-4	0.0080	16.1	0.0472	95.8
B-1	0.0154	30.7	0.008	34.6
B-2	0.0036	7.2	0.006	14.0
B-3	0.0769	153.8	---	---
B-4	0.0052	10.3	0.010	22.5
O-1	0.0190	38.1	---	38.1

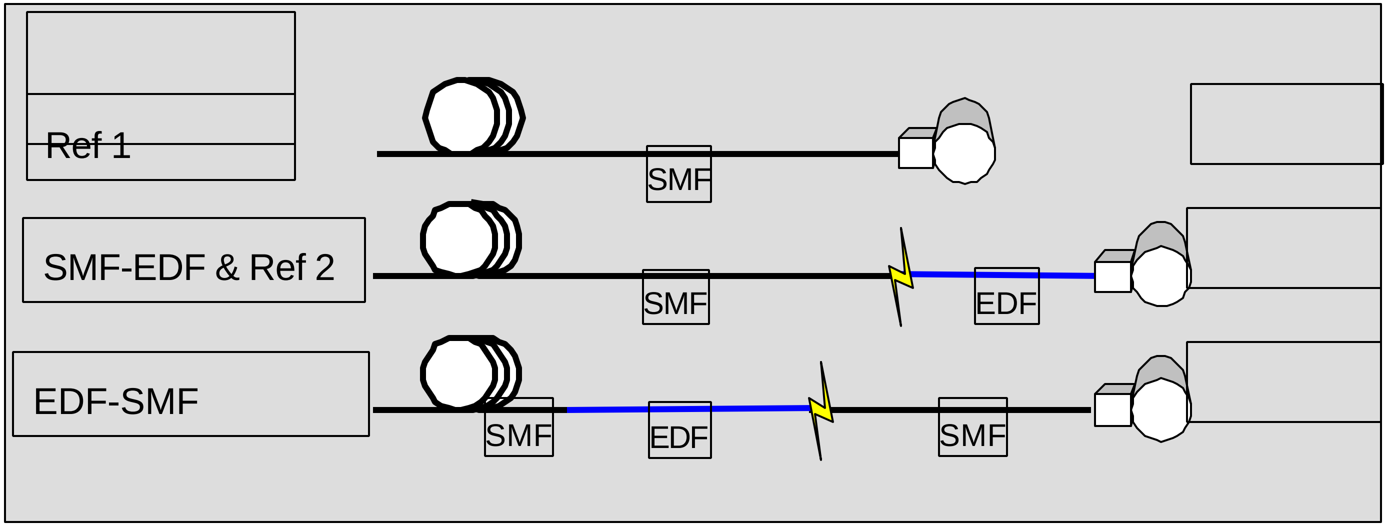
Table 4. Gage R&R Test Results (Two-sided Values)

Splice Measurement Repeatability Gage R&R Study – Conclusions

- Table shows variation within and across 4 In-line methods, 4 BFA and OTDR (users' current set-ups)
- Three test systems/processes are capable of meeting 10% R&R criterion
- Including source stability increases measurement error and only 2 of 9 methods pass 10% criterion
- Within each method there is a large range, e.g. the total process variation for the In-line is 2.4% to 16.1%
- Possibly the best In-line R&R results exceed the best BFA, but more study required using unbiased DOE, control of variables
- Variation in process, due to different splicers & arc parameters, is unknown (this is not expected to be large for SMF-SMF)
- Evident need for more specific standards that detail test methodologies for splice loss. Simply to say that the In-line method being used is not sufficient.
- Confirms need to develop and promote standardized test methods

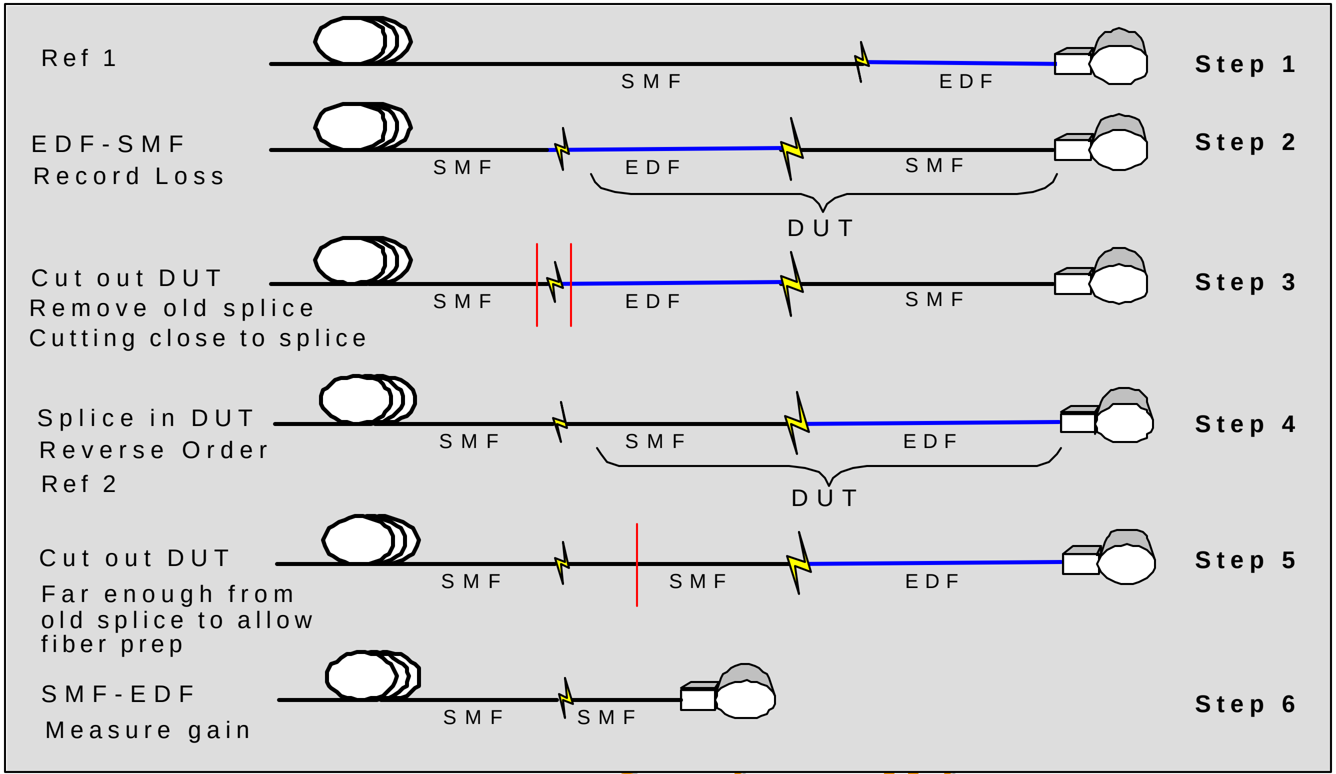
6. Dissimilar Splice Loss Measurement: Option 1

- Make 10 to 30 splices and measurement each splice in one direction, e.g. SMF→EDF or EDF→SMF
- Randomize measurement sequence
- Analyze data by comparing the means of the high & low groups for each user
- May not be possible to combine the data from all users, as values may vary depending on splicer parameters (optimization)

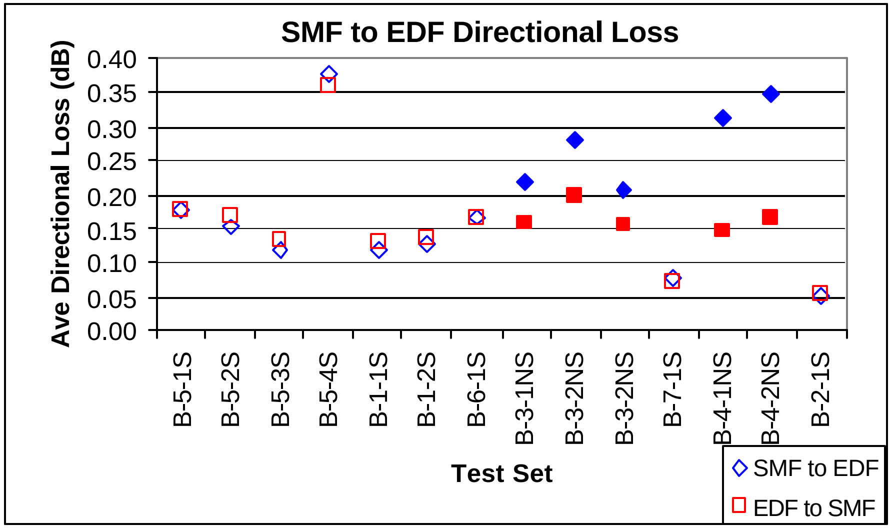


Dissimilar Splice Loss Measurement: Option 2

- Make 10 to 30 splices, and measure each splice in both directions (randomize directions)
- Correct for absorption, if significant (>0.01 dB/m). Measurements at 1310 nm
- Analyze data by performing paired comparison for each user. Compares the deltas in directions for each splice
- Should be possible to combine the data from all users, as well as analyzing each



SMF-EDF Splice Directionality Results



Loss data for SMF-EDF splices, measured in each direction at 1310 nm (using BFA methods 1 & 2). Set-ups B-3 and B-4 without an integrating sphere (NS) are shown as solid symbols.

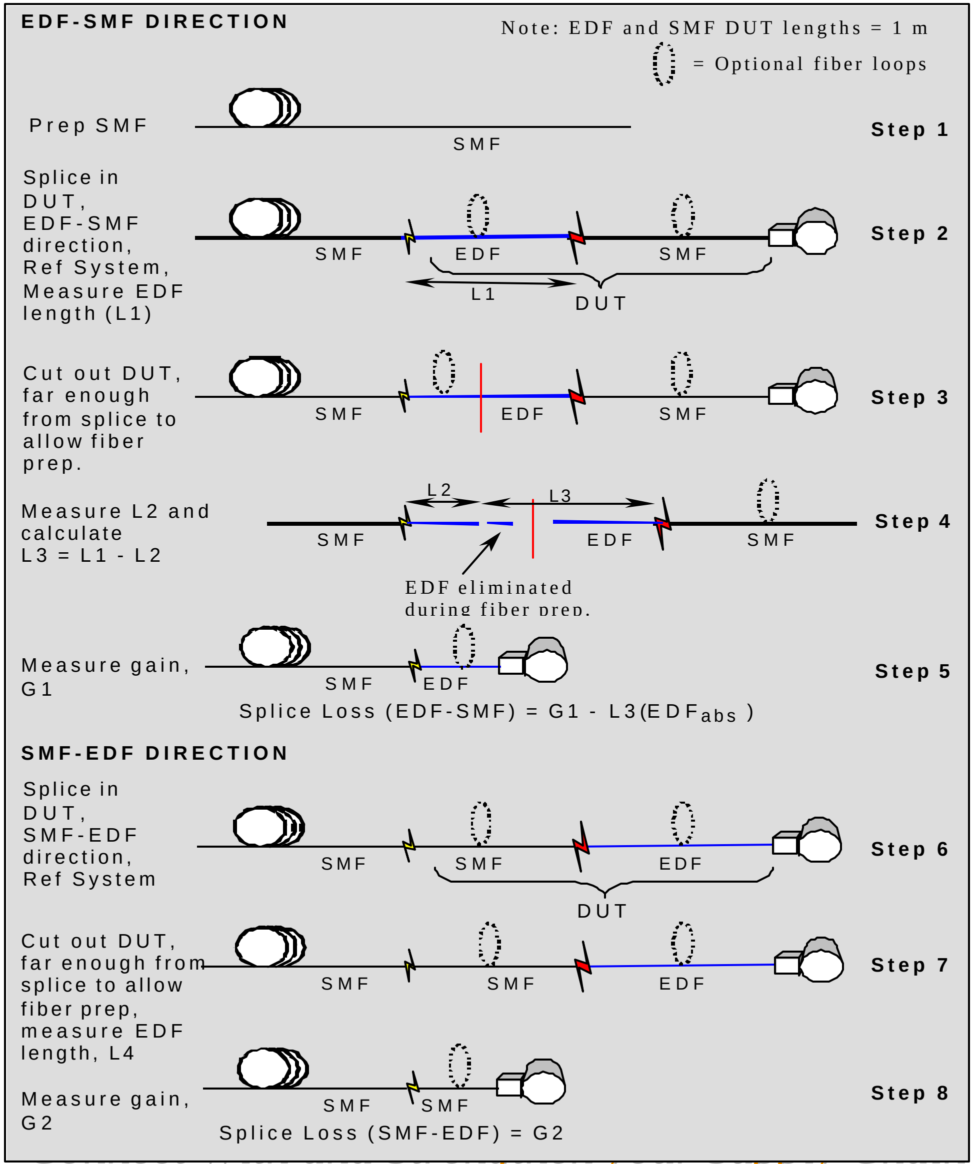
Sample Set	Integ. Sphere	Qty	SMF-EDF Ave (dB)	SMF-EDF StDev (dB)	EDF-SMF Ave (dB)	EDF-SMF StDev (dB)	Directionality (dB)
B-5-2S	Y	11	0.1519	0.0546	0.1691	0.0187	0.0172
B-5-3S	Y	10	0.1192	0.0281	0.1313	0.0226	0.0122
B-1-1S	Y	10	0.1186	0.0232	0.1298	0.0233	0.0112
B-1-2S	Y	10	0.1268	0.0250	0.1341	0.0253	0.0073
B-2-1S	Y	10	0.0508	0.0074	0.0545	0.0088	0.0037
B-6-1S	Y	10	0.1659	0.0470	0.1659	0.0425	0.0000
B-5-1S	Y	10	0.1786	0.0131	0.1783	0.0169	-0.0003
B-7-1S	Y	6	0.0788	0.0114	0.0732	0.0108	-0.0057
B-5-4S	Y	9	0.3778	0.0444	0.3600	0.0194	-0.0178
B-3-3NS	N	15	0.2080	0.0430	0.1560	0.0327	-0.0520
B-3-1NS	N	10	0.2193	0.0517	0.1590	0.0330	-0.0603
B-3-2NS	N	30	0.2790	0.0220	0.1983	0.0280	-0.0807
B-4-1NS	N	10	0.3142	0.0438	0.1454	0.0198	-0.1689
B-4-2NS	N	10	0.3478	0.0196	0.1655	0.0162	-0.1823

SMF-EDF splice loss data ranked by directionality (EDF ® SMF minus SMF ® EDF) showing dependence on use of integrating sphere, "S" with and "NS" without.

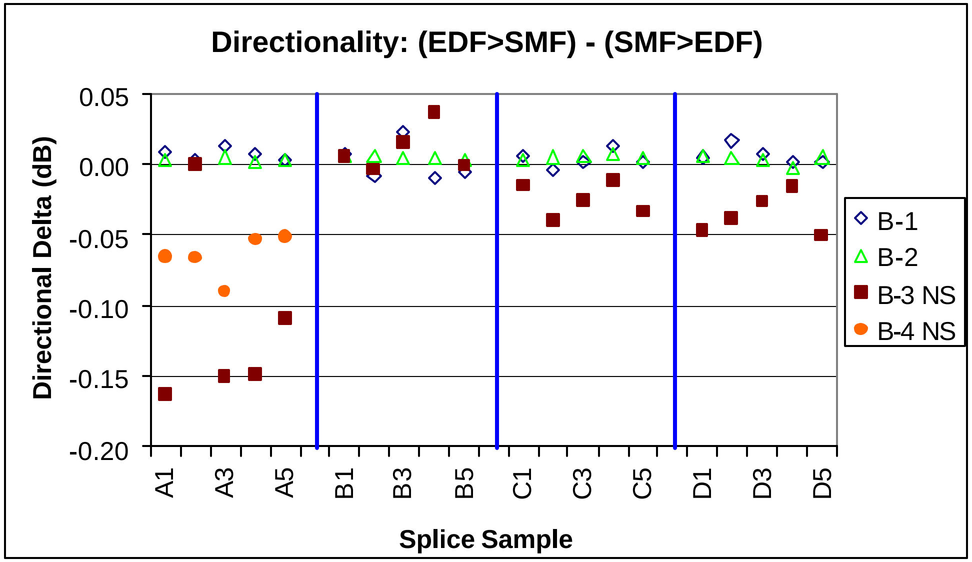
SMF-EDF Loss Measurement

- Some users found significant directional difference, SMF-EDF direction has higher loss
- Average loss (both directions) similar for users with small and large deltas
- One set-up used with & without fiber loops (high order mode stripper) -- no significant difference
- Directionality impacts any proposed standard measurement method
- Cause may be with measurement set-up, fiber type(s) and/or splice
- Investigated further by round-robin measurements
- Three users each made at least 5 splice sections, measured all splices
- Site-to-site method allows each splice section to be measured in both directions (paired comparison) without destroying the original splice

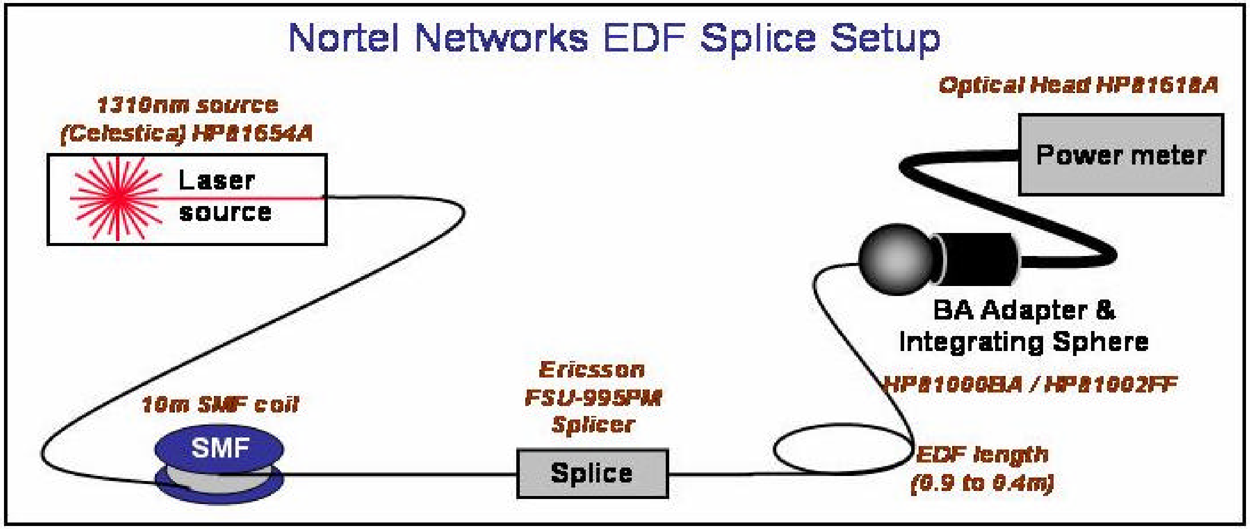
7. SMF-EDF Splice Repeatability: Site-to-Site Round Robin Method



SMF-EDF Splice Round Robin Results



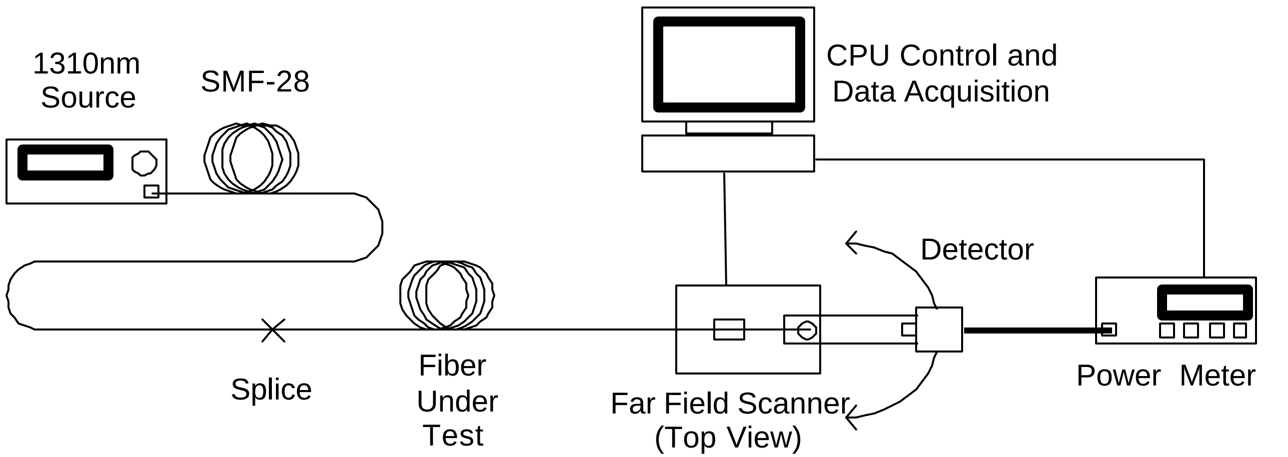
Round-robin directional data for SMF-EDF splices at 1310 nm (using BFA site-to-site method). A to D are fiber combinations and B-1 to B-4 are user test setups.
The largest in directionality is found for user set-ups B-3 & B-4, both without an integrating sphere.



SMF-EDF Splice Loss -- Interim Conclusions

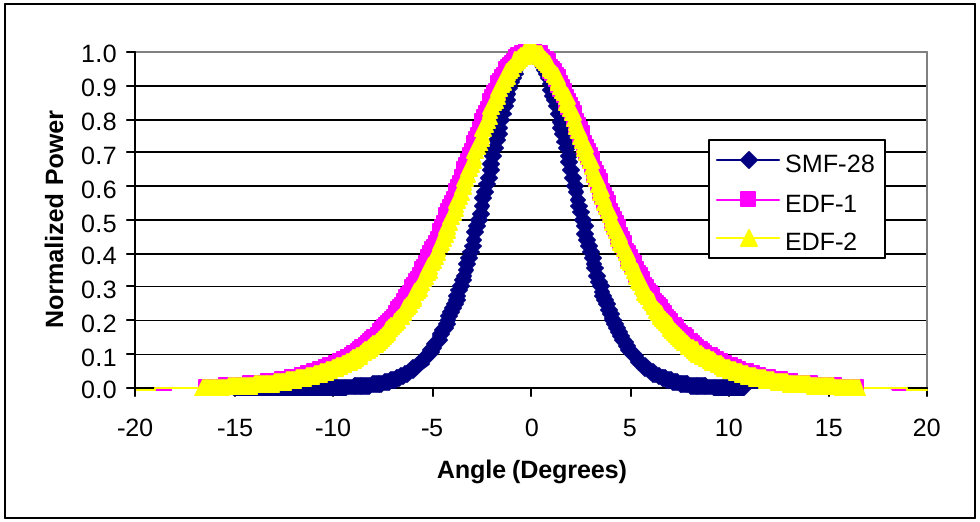
- BFA method at 1310 nm is capable for dissimilar splice loss measurement, with losses >0.1 dB (R&R data shown in paper)
- No published directionality data, but theory predicts no delta for fiber with pure Gaussian mode fields
- Hence directionality dependence is not expected and had to be investigated
- Round-robin indicates directionality may depend on measurement set-up
- Directionality correlates with lack of integrating sphere
- SMF$\rightarrow$EDF direction shows highest loss where there is a delta
- Measured far field intensity distribution at bare end of SMF-28 and EDF to investigate root cause (independent method)

SMF-EDF Splice Directionality: Far Field Intensity Distribution



The 1/e^2 points of the intensity distribution give the numerical aperture (NA) of the fiber. The mode field diameter (MFD) is µ 1/NA.

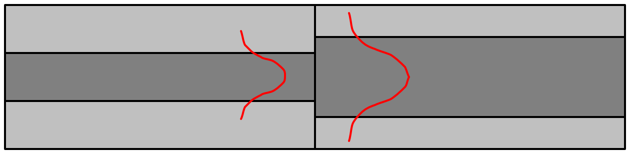
The EDF has smaller MFD and larger NA than SMF-28.

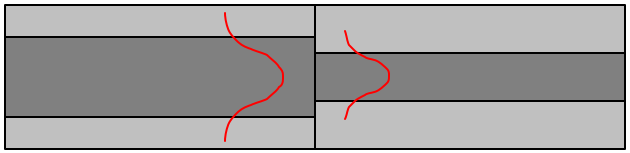


SMF-EDF Splice Loss -- Final Conclusions

- Light emitted from the EDF has a larger cone (NA) cf. SMF-28
- The integrating sphere collects a fraction of all the emitted light, independent of angle
- In the absence of the IS some of the light emitted at higher angles may not be coupled onto the detector, or be detected as efficiently
- Hence highest loss occurs when EDF is coupled to the detector
- Directionality is an artifact of the measurement set-up
- Users need to be aware of the issue and take corrective action
- For example, measure the EDF→SMF direction, measure both directions and average, and/or use an IS
- Even with a directional system, the sum (average) of the two directions gives the same/“correct” value for the splice loss (verified w/site-to-site)

MFD Mismatch:
The Water Bucket-Hose Analogy





The “Hose and Bucket” analogy does not hold water!

8. Standards Organization Liaison

IEC SC 84A fibers, SC 86B (Bruce LeFevre) fiber optic interconnecting devices and passive components

- WG1 (Al Cherin): fibers and and associated measuring methods
- WG4 (Ton Bolhaar): stnd. test and measurement methods for f-o interconnecting devices & passive components
- WG6 (Philip Longhurst): stnds and specs for f-o interconnecting devices
- WG7 (Andre Girard): fiber optic passive components

TIA SC FO-4 (Chair, Steve Swanson) fiber optic components/sub-systems

- FO 4.3 (Tom Ball, Matt Brown): interconnecting devices and related components
- FO 4.8 (Andre Girard): passive f-o devices
- TIA has proposed NEMI representation on U.S. TAG

IPC STD 0040-302 fiber splicing & test (in preparation)

Planned & Possible Follow-on Activities

- Verify test methods for dissimilar fiber splices, SMF28-X (X = EDF, LEAF, high NA)… currently in-progress (#9)
  - BFA/single cut-back, add-on fiber, inserted section methods
- Write project report
- Project completion 1Q'04
- Form follow-on project (with IPC/TIA/IEC) to develop loss measurement standards
  - low loss SMF-SMF splicing and dissimilar fiber splices
- Splicer estimator accuracy metric, based on confidence limits
  - Splice SMF at limits of MFD, core concentricity, eccentricity and batch-to-batch variation, depending on interest
- Low loss standard "splice" for accuracy assessment, with NIST

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Thank You
Fiber Splice Improvement Project