Insertion Loss Measurement of Low Loss Fiber Optic Splices

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 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. An industry standard gage repeatability and reproducibility (GR&R) analysis was used to compare the data. Loss measurement set-ups based on a cutback method for dissimilar fiber (SMF-EDF) splices showed significant directionality in some cases, and root cause was identified using a round robin approach. Several of the methods evaluated will form the basis for a new loss measurement standard for low-loss and dissimilar fiber splices.

INTRODUCTION

For many Optoelectonic manufacturing (OEM) applications, such as EDFA assembly, the ability to fabricate low loss fusion splices is critical for proper function of the optical circuit. Splice loss requirements of less than 0.05 dB are common. While the interdependence of the factors that that cause variability in splice loss have been reported [1-3], at these very low loss requirements, the measurement uncertainty can be a significant problem in determining whether or not a splice is acceptable. Because it is usually not possible or practical to perform actual splice loss measurements during production builds, it is typically necessary to rely on the loss estimation provided by the splicer. To assess the accuracy of splice loss estimators at these low loss levels, a measurement system must be capable of repeatability and reproducibility (R&R) value of ±10% of the range, or ±0.005 dB. Further measurement uncertainty arises in dissimilar fiber splices, where directionality can be observed.

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. A comprehensive review and gap analysis of industry standards relating to splice loss acceptance and test methods revealed that most of these standards were developed for outside plant (field) splicing applications, where loss ranges of over 0.30 dB were acceptable. [4] While TIA 455-34A [5] comes closest towards addressing the needs for a precision loss measurement method, there are important omissions for OEM splicing, e.g. measurement methods for splicing dissimilar fibers, such as SMF to EDF. The objectives of the NEMI 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 splice losses 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.

EXPERIMENTAL METHODOLOGY

Gage R&R Test Method

To quantify and compare the capability of current splice loss test methods, a gage repeatability and reproducibility (GR&R) study [6] was conducted on several optical test system using various loss ranges and fiber types. This investigation required the production of 5-10 splices for a given process range. Each splice was measured three times, using 1-3 operators in a random order, resulting in 3-9 measurements per splice. The spliced fiber was moved between each measurement to introduce any additional variation that would normally occur during the splice. 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. The measurement spread divided by the measurement range (either the actual range or a defined process or tolerance range) gives the gage R&R. 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. [6]

Loss Measurement Methods

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: the in-line method, Figure 1, where the fiber ends remain fixed throughout the entire testing process, or the or the “cutback” method, Figure 2, where the connection to the power meter is changed during the measurement. For this paper we refer to the cutback method as the Bare Fiber Adaptor (BFA) method, in reference to the need for connecting a free fiber end into the power meter detector. Both methods begin with setting up a reference fiber, then measuring the splice loss compared to the reference. If the fiber under test has significant loss, compensation must be included. The test methods used in this study, summarized in Table 1, were further divided between those that accommodate similar and dissimilar fibers. Dissimilar fibers typically have different mode field diameters (MFD), which can result in significant contribution to the splice loss, according to Equation 1 [7, 8].

$$\mathrm{Loss(dB)} = -20\log\left(\frac{2 * \mathrm{MFD}_1 * \mathrm{MFD}_2}{\mathrm{MFD}_1^2 + \mathrm{MFD}_2^2}\right) \qquad (1)$$

There are several setup variations that may make both the in-line and BFA methods more repeatable. These include using cladding mode strippers (per TIA 455-34A), external isolators and securing fibers to prevent unnecessary movement. Within the BFA measurements, distinction was also made between systems that incorporated an integrating sphere (IS), which ideally removes any measurement dependence on how the fiber is coupled to the detector.

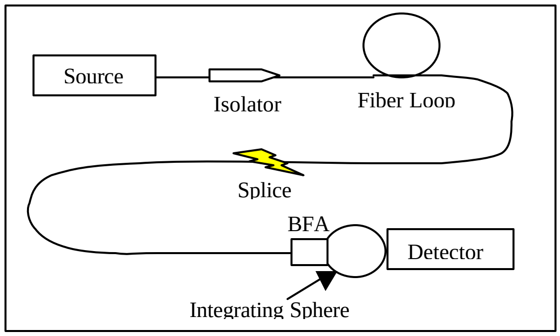

Figure 1. In-line method (I) for similar fibers (BFA and IS optional)

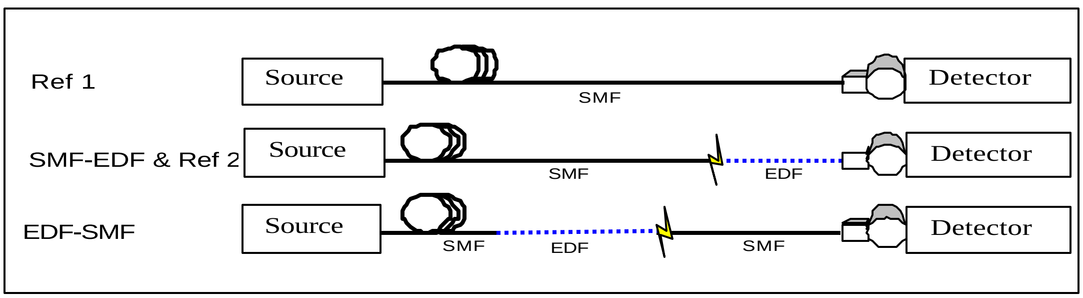

Figure 2. BFA method (B) setup for measuring dissimilar fibers in two directions (SMF and EDF shown)

Table 1. Splice loss measurement methods

Loss Test Method	Fiber Type(s)	Procedure	Attributes
In-line (I)	Similar	See Fig. 1. Initial setup consists of a reference fiber between an optical source and a power meter. The system is allowed to stabilize, the meter's wavelength is matched to the source and the meter referenced. The fiber is cut and spliced back together, with the new power meter reading representing the splice loss. [9]	Fiber ends at source and detector remain fixed throughout. BFA not required.
Bare Fiber Adapter (BFA) "cut-back" (B)	Similar or dissimilar	See Fig. 2. Fiber end at the power meter is prepared and inserted into the BFA. The BFA is inserted into the detector or integrating sphere and the power meter referenced (1st stage). Next, the fiber is removed from the BFA. A piece of test fiber cut, prepared at one end and inserted into the BFA. The other end of the test fiber is spliced to the reference fiber. The new reading on the meter indicates the splice loss (or the combined splice and fiber losses). A second length of test fiber may be added to enable measurement in the other direction (3rd stage).	Different splices required to make measurements in each direction. Absorption correction required if test fiber has non-negligible loss. Integrating sphere recommended.
OTDR (O)	Similar (not evaluated for dissimilar)	Use of an OTDR for fusion splice evaluation is described in Telcordia GR-765-CORE and in detail in TIA/EIA fiber optic test procedures (FOTP) 455-8 and 455-59. [10, 11]	OTDR is continuously self-referencing so the long term stability of the optical source is irrelevant. Long fiber lengths required .
Directional BFA (D)	Dissimilar	Modified BFA method, based on Fig. 2, for each direction. The splice section remains intact. For details see Appendix C of Ref. 4.	Measurement of same splice in each direction enables a paired comparison assessment of directionality.
BFA with add-on (A)	Dissimilar	See Fig. 2, 3rd stage. The system is referenced with the test fiber, a length of reference fiber (with negligible loss) is spliced on and the loss measurement made.	Single loss direction only, e.g. test-to-reference fiber. Absorption correction not required.
Inserted section (S)	Dissimilar	Start as In-line method, Fig. 1. The fiber is cut 1-2 m from end, a length of test fiber is spliced in and the measurement made.	Fiber ends remain fixed. Two splices, each direction, measured in aggregate.

RESULTS AND DISCUSSION

Gage R&R for Similar Fiber Splices

Test setups representing the In-line, BFA and OTDR methods were compared amongst different participants (users), using the Gage R&R stability and repeatability metrics. Table 2 provides a summary of the results for the lowest loss range investigated (0-0.05 dB). Based on the % R&R data, only 5 of the 9 methods were able to meet the 10% threshold and obtain a rating of "adequate". The addition of stability results further degraded the performance with only two of the methods meeting the 10% threshold. Significant levels of variation were seen across and within each test method. For example, even within the in-line test method, results varied by a factor of three or more, with %R&R variations 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.

Table 2. Gage R&R test results for standard SMF similar fiber splices (two-sided values). The setups are described in Table 1.

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

Table 3. Gage R&R results for SMF-EDF splice loss measurements at 1310nm (two-sided). Values for each direction are combined.

Test Method	Test Setup	Max GR&R (%)	Min GR&R (%)	Avg. GR&R (%)
D	B-1	8.8	7.8	8.3
D	B-3	4.5	3.0	3.7
B	B-4	1.5	0.9	1.2
D	B-4	1.6	1.5	1.6
D	B-5	3.0	1.5	2.2
D (EDF2)	B-5	3.0	0.0	1.5
D	B-6	4.6	3.4	4.0

Gage R&R for Dissimilar Fiber Splices

The two BFA-cutback methods (methods B and D, Table 1) were assessed using gage R&R for EDF to SMF fiber splices. The values shown in Table 3, based on a typical loss process range (tolerance) of 0.2 dB for SMF-EDF, indicate both methods have acceptable measurement repeatability for this range of interest. The contribution to the variation from stability (not shown in Table 3), would approximately double the R&R values (cf. Table 2).

Effect of Measurement Direction and Other Variables

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. 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 given by Equation 1. 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.

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 3. The divergence of the data sets indicates that some users observed significant measurement directionality, well above the measurement standard deviation.

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. There was complete separation between set-ups that utilized an integrating sphere and those that did not. One user made measurements with and without fiber loops and did not observe any significant difference in directionality. Since the directionality finding was unexpected, the cause was investigated by means of a round-robin study, whereby splices made by several users are measured on all the various set-ups.

Round-Robin Study

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 (method D). The directional results (Figure 4) 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.

The loss values measured in the round-robin were also compared by averaging the two directional values for each splice. The good agreement (within 0.05 dB) between different users further supports that the observed directionality is a measurement artifact, and not a 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.

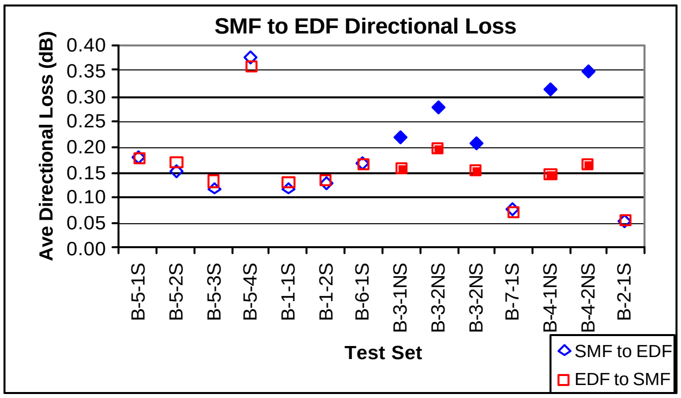

Figure 3. Loss data for SMF-EDF splices, measured in each direction at 1310 (method B and D). Set-ups B-3 and B-4 are without integrating sphere (NS).

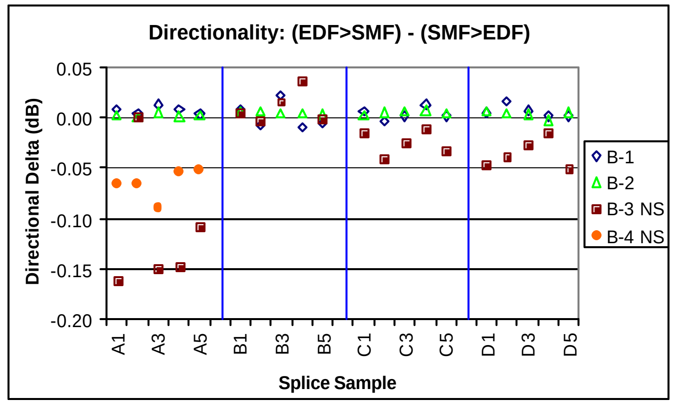

Figure 4. Round-robin directional data for SMF-EDF splices, at 1310 nm. A-D are fiber combinations and B-1 to B-4 user test set-ups.

Field Intensity Distribution Measurement

Far field intensity measurements for both the erbium doped fibers, as well as standard SMF, showed that at high angles of incidence, both of the EDF fibers have a significantly broader far field pattern compared to standard SMF. [4] 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. 12 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 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. 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.

Verification of Test Methods for Dissimilar Fiber Combinations

The BFA add-on (A), directional (D) and inserted section (S) are suitable loss methods for dissimilar fiber splices and these were further evaluated using fiber types with substantially different MFD from standard SMF. The results are shown in

Table 4. Here the precision (defined as measurement error divided by the average loss for the data set) is based on the tolerance method because the splice loss varied widely for the different fiber types and users. Loss values for method S were halved to give the average loss per splice. The methods have acceptable repeatability (<5%) and they are candidates for inclusion in the proposed new standard.

Table 4. Loss values for various fiber combinations and user set-ups for three methods. HNA (High NA) and LEAF refer to different types of fiber. PDL and Pwr are the polarization dependent loss and power modes of the test equipment.

Method	Fiber Combination	Wavelength (nm)	User	# Parts/ Appraisers	Avg Loss (dB)	GR&R +/-Error (dB)	Relative +/-Error (%)
A	EDF1-SMF	1550	B	10/2	0.1163	0.0072	6.2
A	EDF2-SMF	1550	B	10/2	0.1988	0.0068	3.4
A	EDF2-SMF(PDL)	1550	B	5/1	0.2445	0.0033	1.4
A	EDF2-SMF(Pwr)	1550	B	5/1	0.2355	0.0038	1.6
D	HNA-SMF SMF-HNA	1310	B	6/1	0.2504 0.2534	0.0067 0.0057	2.7 2.3
D	LEAF-SMF SMF-LEAF	1550	B	5/1	0.1285 0.1239	0.0074 0.0050	5.8 4.1
S	SMF-HNA-SMF	1310	B	10/1	0.2384	0.0189	7.9
S	SMF-HNA-SMF	1550	B	10/1	0.2452	0.0059	2.4
S	SMF-HNA-SMF	1310	D	10/1	0.7006	0.0016	0.2
S	SMF-HNA-SMF	1550	D	10/1	0.5914	0.0018	0.3
S	SMF-LEAF-SMF	1550	B	10/1	0.1017	0.0042	4.1
S	SMF-LEAF-SMF	1550	D	10/1	0.1126	0.0019	1.7
S	SMF-HNA-SMF	1310	F	10/1	0.6060	0.0050	0.8
S	SMF-LEAF-SMF	1550	F	10/1	0.1275	0.0050	3.9

CONCLUSIONS

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 optoelectronic 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 often be 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.

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.

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