Using the OBR with Multi-Mode Fiber

Contents

www.lunainc.com

3157 State Street | Blacksburg, VA 24060

solutions@lunainc.com

Support phone: 1.866.586.2682

1 Introduction

Luna Technologies' Optical Backscatter Reflectometer (OBR) is ideally suited for measuring Insertion Loss (IL) and Return Loss (RL) in optical networks with extremely high spatial resolution.[1,2] Because the OBR operates on the principle of swept laser interferometry, fiber used in the instrument is single-mode in order to maintain optimum interferometer performance. The test fiber, however, may be either multi-mode or single mode. As with all multi-mode fiber testing, results may vary on the mode launch condition. This engineering note details two alternate methods of coupling light from single mode fiber to multi-mode fiber in a controlled and consistent manner which both produce stable and repeatable IL and RL results. This note also discusses the differences between IL and RL results for the two launch conditions and details the consequences for OBR spatial resolution so that the user may choose the launch method which best suits their application.

2 Basics of Light Propagation in Multi-Mode Fiber

Multi-mode fiber (MMF) is generally distinguished from single mode fiber by a significantly larger core size. Fifty and 62.5 micron core diameters are typical for multi-mode communications applications, compared to the 8 micron core diameter more typical of single mode fiber (SMF). The larger core size of MMF has several advantages, including less stringent manufacturing tolerances, less stringent spatial alignment tolerances for connectors and splices, greater coupling efficiency with inexpensive light sources such as LEDs and VCSELs, and higher power handling capability. These advantages can lead to lower system installation and maintenance costs. The principle drawback of MMF is that the various modes supported by the fiber in general have different propagation rates. This difference in propagation rates causes light, which starts out at the same time but in different modes, to arrive at different times at the fiber termination. This phenomenon is known as modal dispersion.

The magnitude of modal dispersion is highly dependent on the core index of refraction profile. Multi-mode fiber is manufactured with one of two different core profiles: step-index or graded index (shown in Figure 1). Step-index MMF is simpler to manufacture but has higher levels of modal dispersion than graded-index fibers. If the index of refraction of the core can be made to have a near parabolic profile, modes which travel near the center of the core travel with nearly the same group velocity as modes which travel near the core-cladding interface and modal dispersion is greatly reduced. Step-index MMF is still used in high power handling applications and in some legacy communications applications, but graded-index multi-mode fiber dominates new short range telecommunications applications because its lower modal dispersion allows it to support much higher data rates over longer distances. These short range applications typically include networks employed on ships and aircraft, corporate intranets, and increasingly in local fiber-to-the-home installations. Because of the growing preference towards graded-index MMF we concentrate our discussion of the OBR's multi-mode measurement characteristics to this sub-type, although qualitatively the behavior of step-index MMF is similar.

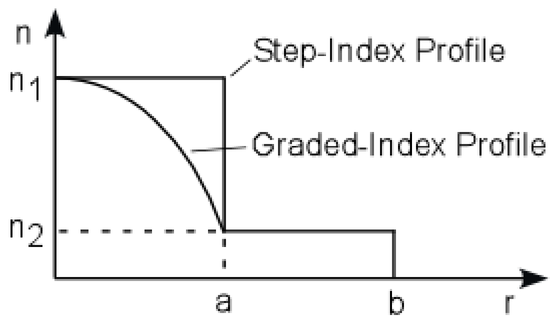


Figure 1. Index of refraction, n, profile as a function of fiber radius, r, showing the difference between step-index and graded-index MMF. Modes are bound within the core radius r = a by the index of refraction difference between core and cladding of n_1-n_2.

Drawing individual modes as propagating rays is a useful construct for describing mode behavior. Figure 2 shows 3 rays which emanate from an LED and are injected into a graded-index MMF. The ray along the optical axis of the coupling lens couples into the lowest order mode which propagates down the axis of the fiber. Rays that depart the LED at higher angles couple into higher order modes which oscillate back and forth across the fiber axis. Generally higher order modes are described by rays that have a longer path length but travel through sections of the core that have a lower index of refraction than lower order modes. If the core index has a parabolic profile, the product of the path length and the average index of refraction is nearly equal for all of the modes and modal dispersion is minimized. Figure 2 only shows meridional modes which pass through the fiber axis; another class of modes known as skew modes propagate in a helical fashion down the fiber core without crossing the fiber axis.

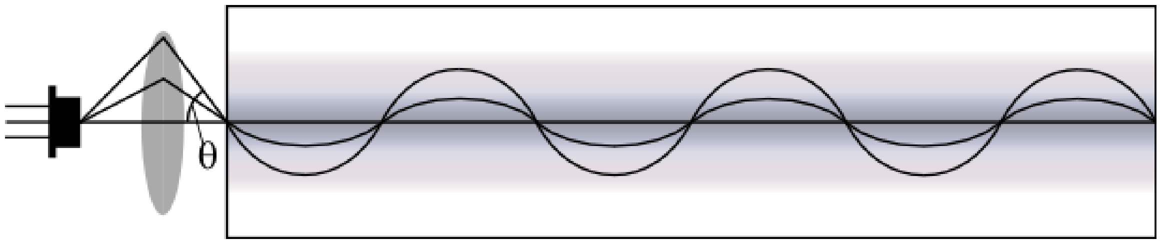


Figure 2. Light from a packaged semiconductor light source, such as an LED, is collected by a lens and injected into a graded-index MMF. Three rays are shown: one ray along the fiber axis which depicts the lowest order mode and two rays with higher angles of incidence θ which couple into higher order modes that travel closer to the core-cladding boundary.

The numerical aperture (NA) of a fiber is defined as the sine of the maximum angle of incidence θ_c at which light can couple into the fiber core modes. The NA is related to the index of refraction of the core and cladding as follows:

$$NA \equiv \sin(\theta_c) = \sqrt{n_1^2 - n_2^2} \tag{1}$$

The NA for multi-mode fiber is typically higher than for single mode fiber. For example, NA = 0.275 for Corning InfiniCor 300 multi-mode fiber, but NA = 0.14 for Corning SMF-28E single mode fiber. Thus, when light from a SMF is launched into a MMF, typically the low order modes are favored and almost no light is launched into the high order modes.

A useful parameter used when designing single mode and multi-mode fibers is called the "normalized frequency" or "V-number" and is calculated as:

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \tag{2}$$

Modes may be described mathematically by solving the wave equation in cylindrical coordinates. Each discrete solution found has a threshold V-number; if the fiber V-number is larger than the threshold for a particular mode, that mode will be supported by the fiber. Thus the higher the fiber V-number the more modes are available to populate. The number of modes N_M which may propagate in a particular fiber is roughly proportional to the square of the V-number:

$$N_M \approx \frac{V^2}{4} \tag{3}$$

Thus the number of modes available to populate is proportional to the square of both fiber diameter and NA and inversely proportional to the square of the center wavelength. Typically graded index multi-mode fiber for communication applications supports over 100 modes. Much more detailed mode propagation theory can be found in several recent texts.[3,4]

3 Mode Launching From Single Mode to Multi-mode Fiber: Direct and Mode Scrambler Methods

Because the OBR uses scanning laser interferometry to collect data from the fiber under test, and the interferometer operation is designed to be single mode, single mode fiber must be used in the interior of the instrument. Therefore when the fiber under test is multi-mode there will always be a SMF to MMF transition, and the mode population which results from this transition will affect the RL and IL that light propagating in the MMF under test experiences. In this engineering note we will describe the use of two different mode launch conditions which we will call the "direct launch" and the "mode scrambler launch".

As mentioned in the previous section, a direct splice between SMF and MMF will tend to only launch light into low order modes because the numerical aperture of SMF is much lower than for MMF. The direct launch from SMF to MMF may be implemented by either a splice between the two fibers or a direct connection (as shown in Figure 3). The mode launch from a SMF to MMF splice is more repeatable than between two connectors, but for most practical purposes the two implementations are equivalent. The IL for such a splice or connection is surprisingly low, typically less than 1 dB. Note that the mode coupling efficiency condition of the direct launch holds for light returning to the instrument: light which has remained in the low order modes couples efficiently to the SMF core, while any light which leaks into the higher order modes will not couple back as efficiently. Thus a direct launch between SMF and MMF has mode filtering properties.

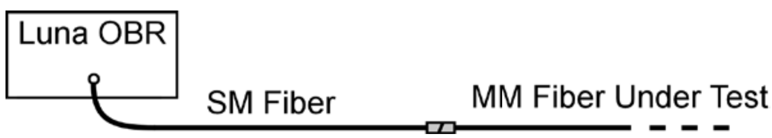


Figure 3. Direct launch from single mode to multi-mode fiber.

The other mode launch method we consider in the engineering note utilizes a mode scrambler, alternatively known as a mode controller or mode conditioner. In an ideal case, the mode scrambler couples light from each input mode equally into all output modes and is fully reversible so that light returning to the output port will also be scrambled equally to the all modes at the input port. The ideal mode scrambler produces a uniformly mode filled condition at the output regardless of the mode population at the input. Various mode scramblers are available commercially; the user should be careful to choose one which is designed for the same MMF type as is used for the fiber under test. The mode scrambler launch is implemented by placing the mode scrambler between the SMF connected to the front panel and MMF under test as shown in Figure 4. Unlike the direct launch case, alteration of the mode population in the fiber under test will not necessarily cause light to be lost as all modes should couple back to the instrument with equal efficiency. The most significant downside to using a mode scrambler is that they tend to very lossy; generally the more uniform the mode coupling between the input and output ports the higher the loss. The mode scrambler loss may have consequences for making accurate insertion loss measurements if the loss causes Rayleigh back scatter level to drop close to the background noise level; this condition will be discussed in the next section. Also the length of the leads of the mode scrambler subtract from the total scan length available for the fiber under test.

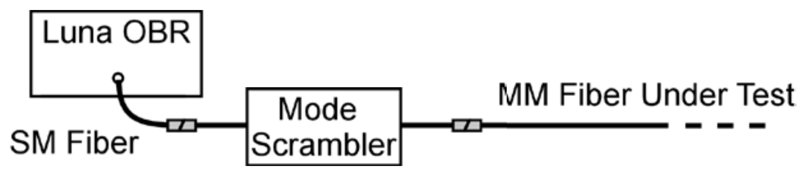


Figure 4. Mode scrambler launch from single to multi-mode fiber.

4 Making Insertion Loss Measurements in Multi-mode Fiber

Since the back scatter level is a constant for a particular fiber type, IL measurements are most easily made by comparing the amplitude of the Rayleigh back scatter before and after the loss event. The loss encountered by light traveling one way across the loss event is one half of the difference in the back scatter level measured before and after the event since the OBR operates in reflection, so the light must transit the loss event twice before returning to the instrument. As an example, we detail the measurement of IL for a splice in MMF midway along a multi-mode jumper using a direct launch and a mode scrambler launch.

4.1 Direct Launch IL Measurement

First we will examine the direct launch case. Figure 5 shows the network diagram of a multi-mode jumper with a splice midway along its length attached to the front panel of the OBR. Figure 6 shows the corresponding upper graph trace from the OBR display resulting from a scan of this jumper. The red and yellow cursors are placed on either side of the splice; the return loss (RL) for scatter level integrated over the width (set by the Integration Width control) of the highlighted portion of the trace for each cursor is shown in the upper right corner of the graph. The reported Differential Loss (in white) is the yellow cursor RL value subtracted from the red cursor RL value divided by 2, and in this case is equal to the IL of the splice for a direct launch. Since the fiber inside the instrument is single-mode, the mode power distribution is determined by the single mode to multi-mode connection at the front panel of the instrument. As previously discussed, the result is that almost all of the instrument laser light is injected into several low order modes which propagate near the center of the multi-mode core.

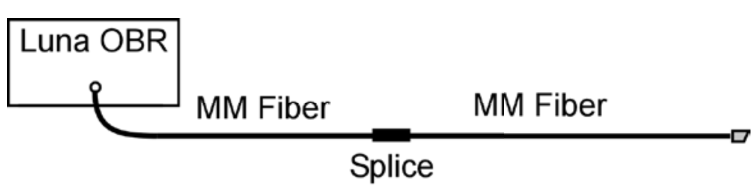


Figure 5. Network diagram of multi-mode jumper connected to the front panel of the OBR with a splice mid-way along its length.

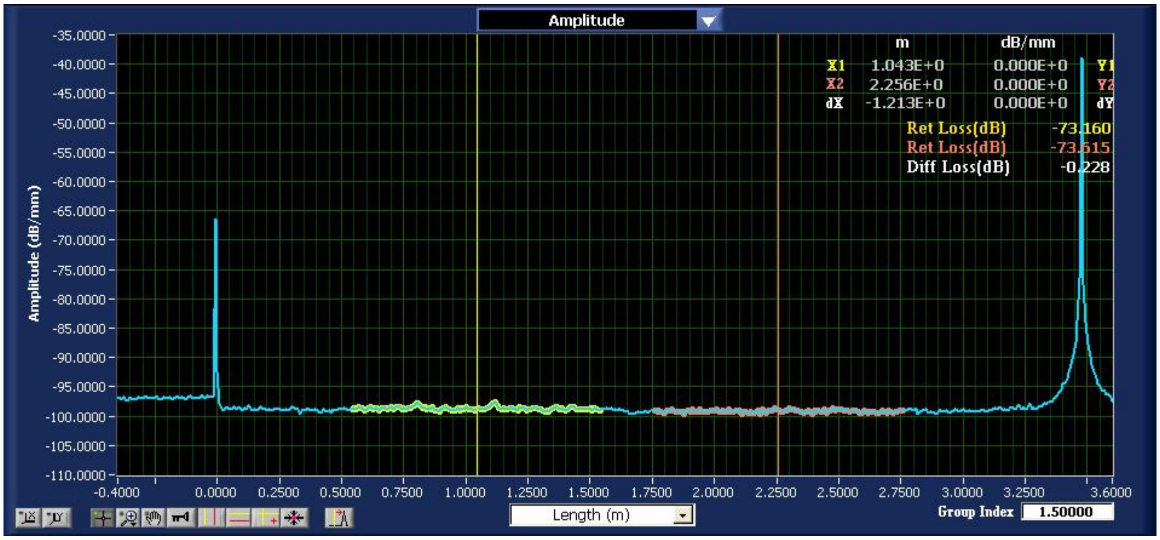


Figure 6. The OBR upper graph trace for the network shown in Figure 5. An insertion loss measurement is performed by placing the vertical cursors before and after the splice.

4.2 Mode Scrambler Launch IL Measurement Mode with Background Subtraction

Alternatively, the mode power distribution in the jumper can be made more uniform by placing a mode scrambler in between the instrument and the multi-mode jumper as depicted in Figure 7. The mode converter used for this study was designed to produce a mode profile which conforms to current multi-mode cable testing standards[5] for the particular fiber used in the jumper. The upper graph of the OBR output for the network in Figure 7 is shown in Figure 8. Note that in this case a small reflection peak is coincident with a drop in the back scatter level at the splice location. The reflection peak appears only when the higher order modes nearest to the defect are populated. The IL measurement is made by placing vertical cursors before and after the splice as before, however in this case the Differential Loss listed in the upper right hand side of the plot is not equal to the IL. Because the mode converter has a high amount of loss associated with it the scatter level in the multi-mode fiber is only a few dB above the noise floor of the instrument. An additional measurement of the background noise level at the same cursor locations as used in Figure 8 is required to get an accurate measure of the IL.

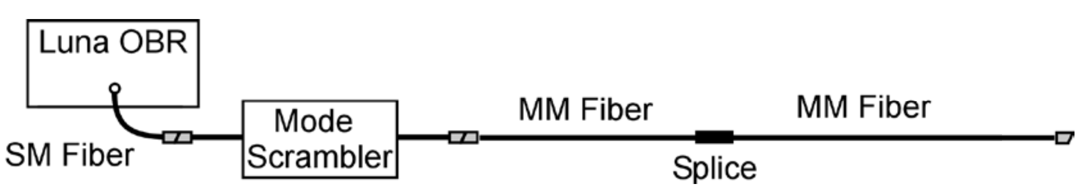


Figure 7. Network diagram of the same multi-mode jumper as in Figure 5 is connected to a mode converter which is in turn connected to the front panel of the OBR

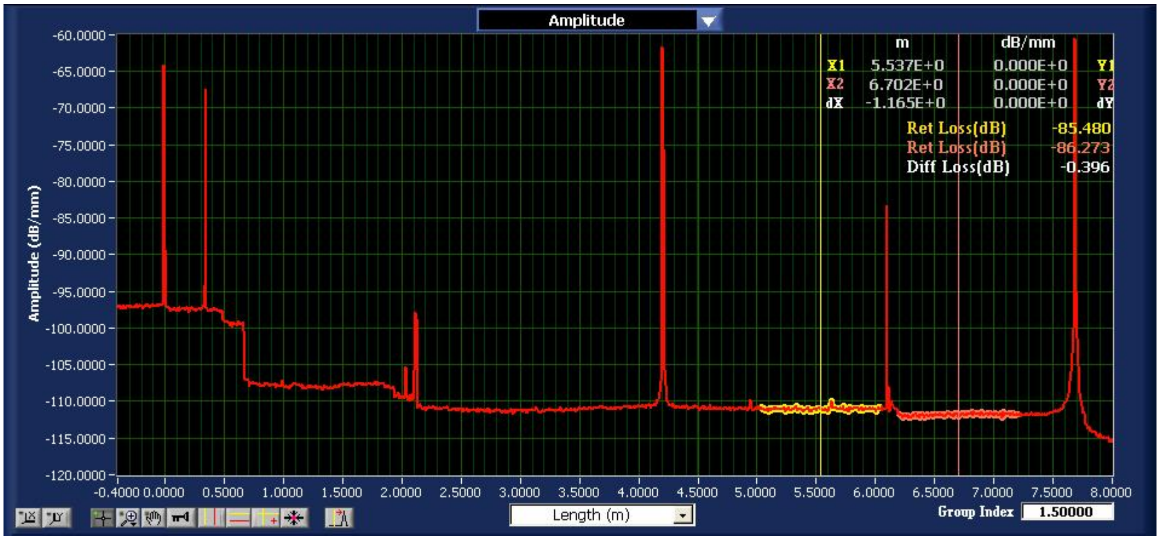


Figure 8. The OBR upper graph trace for the network shown in Figure 7 which contains the splice shown in Figure 5. An insertion loss measurement is performed by placing the vertical cursors before and after the splice and subtracting of the background noise level.

For best accuracy in this case, the return loss noise floor should be subtracted from the return loss values of the fiber scatter levels. The noise floor measurement is accomplished by taking a scan over the same wavelength range at the same detector gain level but with no fiber network attached to the instrument; the resulting trace from such a scan is shown in Figure 9.

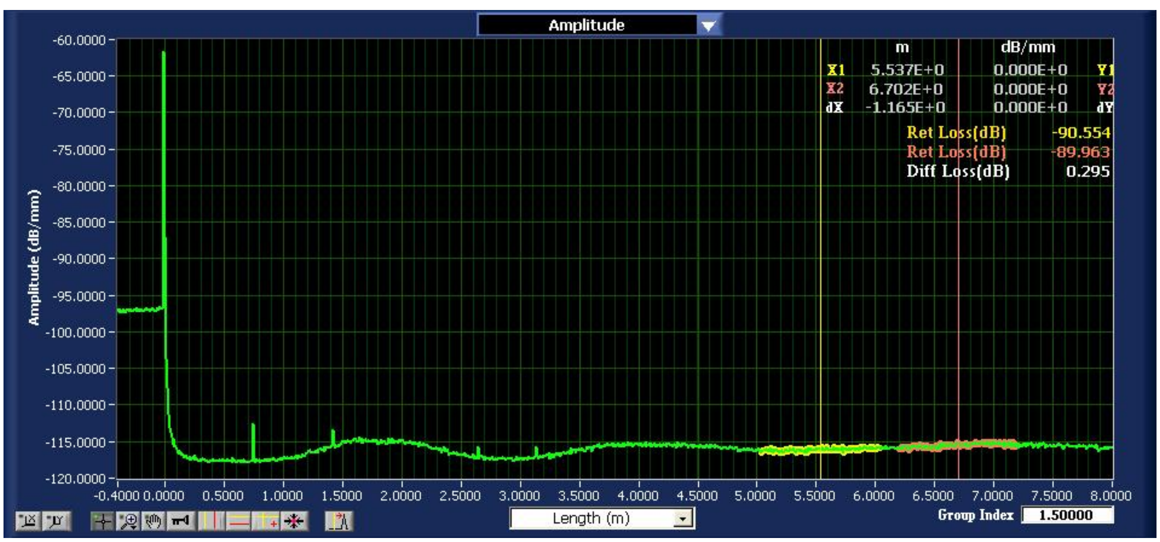


Figure 9. The OBR upper graph trace showing the instrument background noise level. The background return loss of the noise level is measured for the same cursor locations and integration width as used in Figure 8.

If the fiber scatter return loss values before and after the splice are labeled RL_0 and RL_1 and the background noise level return loss values at the same locations are labeled RL_{B0} and RL_{B1}, then the background corrected IL is given by converting the RL values from log to linear amplitudes, subtracting off the background levels, converting the adjusted RL values back to log scale, then dividing the difference by two:

$$IL = \frac{1}{2}\left(10\log\left(10^{\frac{RL_1}{10}} - 10^{\frac{RL_{B1}}{10}}\right) - 10\log\left(10^{\frac{RL_0}{10}} - 10^{\frac{RL_{B0}}{10}}\right)\right) = 5\log\left(\frac{10^{\frac{RL_1}{10}} - 10^{\frac{RL_{B1}}{10}}}{10^{\frac{RL_0}{10}} - 10^{\frac{RL_{B0}}{10}}}\right) \quad (4)$$

Note that our convention is to state both IL and RL as negative numbers. In the example depicted in Figures 8 and 9, the IL without the background correction is -0.40 dB and with the background correction is -0.80 dB. Generally the background noise floor correction to the IL value will be less than 10% when the background noise level is 10 dB below the Rayleigh scatter level. The example above is unusual in that the background noise floor has noticeable ripple; in most cases the background noise floor is flat enough that the same background noise level can be used before and after the loss event.

4.3 Example Results for Insertion Loss Due to Poor Splices

Because higher order modes have different core spatial distributions than low order modes the distribution of modes that are populated when light is launched from the OBR into multi-mode fiber under test may have a large impact on loss measurements. For example, when a multi-mode fiber is bent, light in the highest order modes near the core-cladding interface is most likely to couple to cladding modes which subsequently leak out of the fiber. Thus if launch conditions favor high order modes over low order modes an insertion loss measurement will be more likely to reveal bend loss. Similarly, splices with defects concentrated near core-cladding boundary are more likely to produce loss in high order modes without attenuating low order modes. Examples of such splices are shown in Figures 10 and 11.

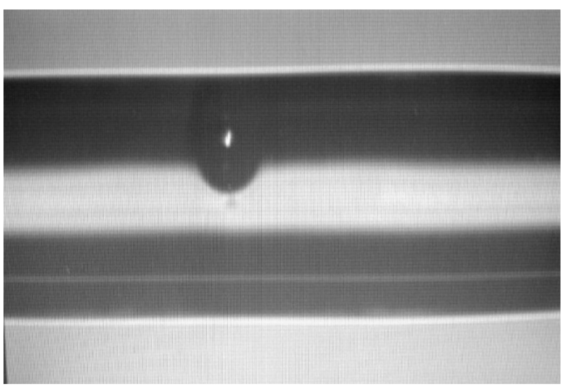


Figure 10. A splice in multi-mode fiber with a bubble near core edge.

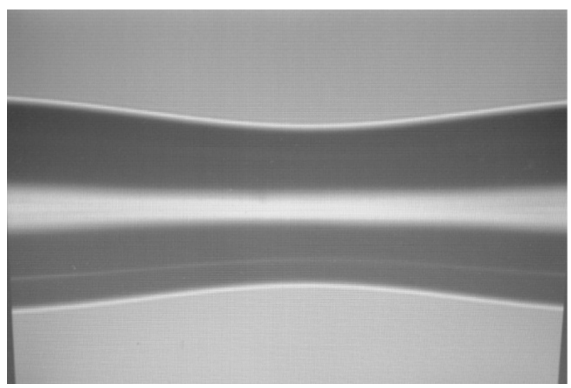


Figure 11. A splice in multi-mode fiber resulting in narrow waist.

OBR IL results for the two splices shown in Figures 10 and 11 are presented in Table 1; OBR traces for a direct launch and mode scrambler launch for the splice in Figure 10 are shown in Figures 6 and 8. The results are compared to the results from a multi-mode power meter which was used to measure the power transmitted through the jumper before and after the jumper fiber was broken and the splices were made. The multi-mode power meter used a fiber coupled LED as the light source. The mode power distribution of this source was not well documented, but LED to multi-mode launches typically insert more power into the higher order modes than the lower order modes. For both splices the measurement made with the mode converter at 1300 nm most closely matches the LED-based multi-mode power meter results. The measurements made without the mode converter showed much lower IL values as expected.

Table 1. Measured insertion loss for two flawed splices.

	Insertion Loss (dB)				
	OBR with direct SMF to MMF launch		OBR with mode converter		LED-based MM meter
Flaw Description	1300 nm	1550 nm	1300 nm	1550 nm	1300 nm
Bubble Near Cladding Boundary	-0.23	-0.20	-0.80	-0.80	-1.03
Narrow Waist	-0.22	-0.12	-0.48	-0.39	-0.62

Conversely, loss events which alter the mode population (such as an offset splice) typically cause much higher loss for measurements made without the mode converter. This is because the launch conditions from a direct single mode to multi-mode fiber splice are highly selective – if the mode profile of the light returning from the far side of a loss event is significantly altered from the input profile there will be additional loss experienced in the transition back from multi-mode to single-mode fiber. If the launch condition is not mode selective (ie. a mode converter is used) the observed loss may be much lower because the mode profile of the light returning to the multi-mode to single-mode interface is almost identical for light scattered back before and after the mode-altering loss event. Thus measurements made without a mode converter are more sensitive to loss events which alter the mode profile. This principle is demonstrated by measuring IL with and without the mode converter for three splices with increasing degrees of linear offset introduced just prior to fusion. Figure 12 shows the placement of the fiber tips for the largest of the three offsets and Figure 13 shows the image of the resulting splice. The IL results for these three splices are presented in Table 2.

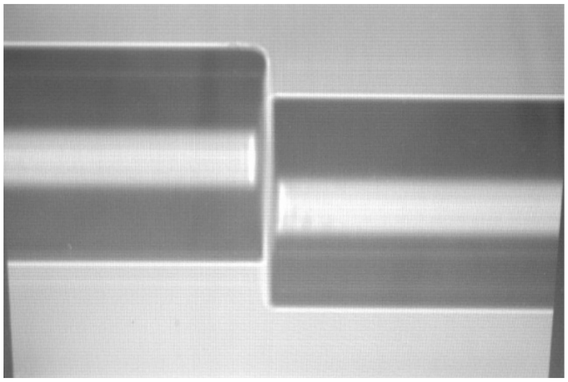


Figure 12. Offset Splice C just prior to fusion.

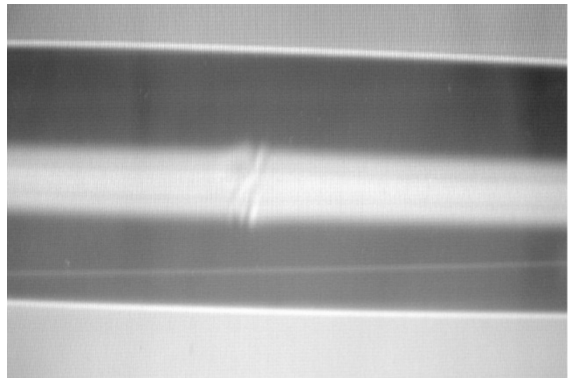


Figure 13. Offset Splice C post fusion.

Table 2. Measured insertion loss for three splices with an increasing degree of offset.

Flaw Description	Insertion Loss (dB)				
	OBR with direct SMF to MMF launch		OBR with mode converter		LED-based MM meter
	1300 nm	1550 nm	1300 nm	1550 nm	1300 nm
Offset Splice A	-0.53	-0.62	-0.42	-0.34	-0.36
Offset Splice B	-1.14	-0.98	-0.50	-0.49	-0.60
Offset Splice C	-2.44	-2.27	-1.23	-1.16	-1.42

As before, the OBR results which most closely match those of the multi-mode power meter were taken using the OBR at 1300 nm with the mode converter in series with the multi-mode jumper. Contrary to the earlier examples, however, the loss reported without using the mode converter shows significantly higher loss (close to a factor of 2) because without the mode converter the measurement system is also sensitive to excess loss produced as a result of changes in the mode profile produced by the offset splices.

4.4 Example Results for Insertion Loss Due to Bending

The IL response to macro-bend in MMF is very similar to that for the bubble splice and waist splice example in Figures 10 and 11. Macro-bend loss is most likely to occur to light propagating in high order modes near the core/cladding interface since light in these modes are more likely to couple to cladding modes and be lost to the environment. Thus we expect that a direct SMF to MMF launch will produce the lowest IL values since very little if any light is launched into high order modes. A uniform mode population as produced by a mode scrambler launch should produce moderate levels of IL. The highest IL should be produced by a launch condition that favors high order modes, such as a typical LED to MMF launch. We also expect the IL to increase with decreasing bend diameter.

To test these expectations we observed the IL resulting from wrapping the fiber around various diameter mandrels five times. The set-up for each measurement case is shown in Figures 14-16, and typical screen traces for the mode scrambler launch are shown in Figures 17 and 18. For the multi-mode meter IL measurement, a reference power reading was taken before the fiber was wrapped around the mandrel, and subtracted from the power transmitted after the fiber was wrapped around the mandrel (Figure 14). The OBR direct launch and mode scrambler launch measurement were taken in reflection after the wrap was applied, as shown in Figures 15 and 16.

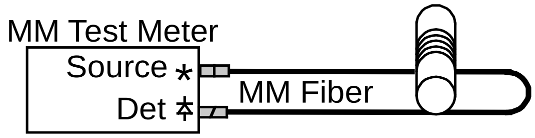


Figure 14. Multi-mode meter measurement of IL due to a mandrel wrap.

Figure 15. OBR direct launch measurement of IL due to a mandrel wrap.

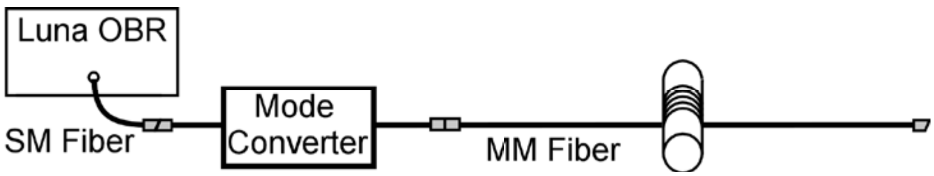


Figure 16. OBR mode scrambler launch measurement of IL due to a mandrel wrap.

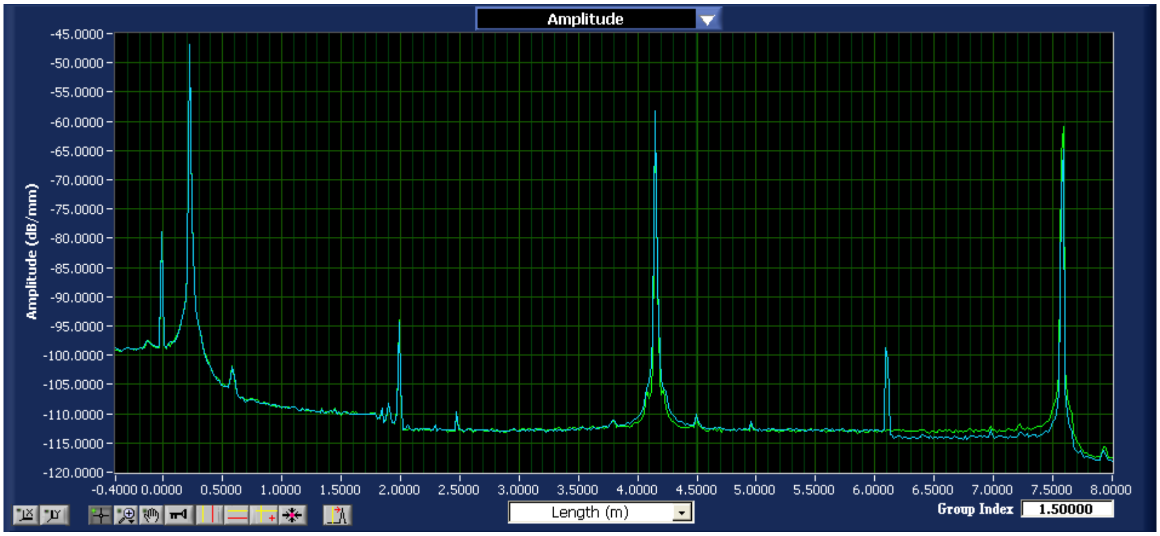


Figure 17. OBR upper traces of the network shown in Figure 16, without (blue) and with (green) a mandrel wrap consisting of one loop around a 7.5 mm mandrel.

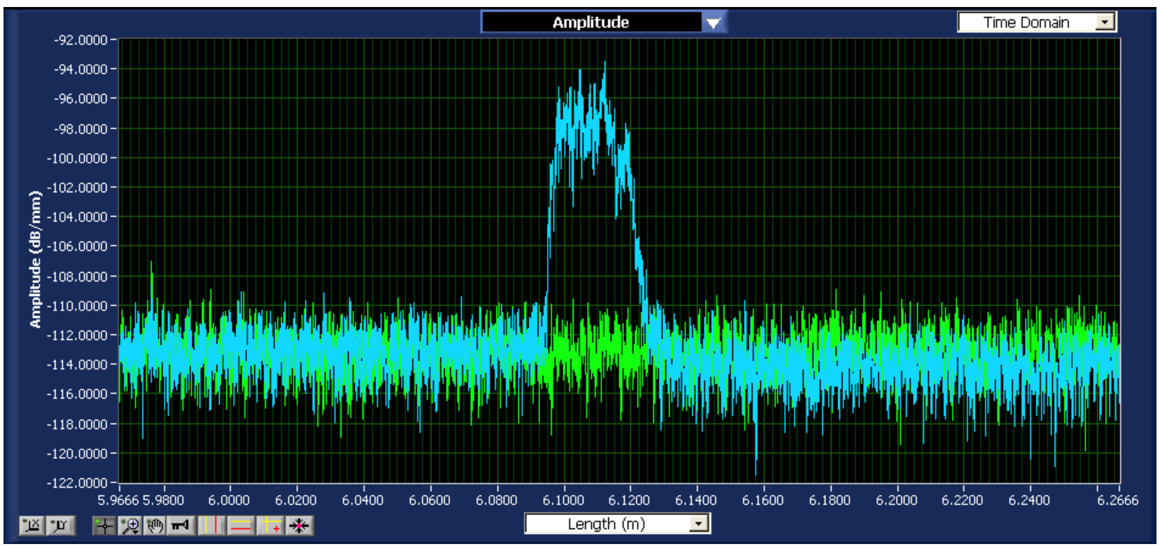


Figure 18. OBR lower trace of the network shown in Figure 16 detailing the scatter signature of the mandrel wrap in Figure 17.

The results of our measurements are summarized in Table 3. As expected, IL increases with decreasing bend diameter, and the launch conditions with higher ratio of power in higher order modes to lower order modes produces higher loss values.

Table 3. Comparison of mandrel wrap Insertion Loss measurements using the OBR with direct mode scrambler launches and a multi-mode meter with LED to MMF launch. The MMF was InfiniCor 300 fiber and all measurements were made at 1310 nm.

Five Mandrel Wraps, Bend Diameter (mm)	Insertion Loss (dB)		
	OBR Direct Launch	OBR Mode Scrambler Launch	MM Meter LED Launch
9.0	0.20	0.84	1.11
10.5	0.13	0.54	0.80
11.5	0.06	0.49	0.72
13.0	0.05	0.16	0.45

5 Making Return Loss Measurements in Multi-mode Fiber

The light returned from a reflection event in the fiber under test is necessarily diminished by the network loss on the path back to the instrument. For many applications the loss associated with the front panel connector or with the direct SMF to MMF launch is small compared to the required RL measurement accuracy and adjustments to compensate for these losses are unnecessary. In this case, the RL can be measured directly, by positioning one of the upper graph cursors over the reflection event in question, adjusting the cursor integration width appropriately, and reading the value from the upper graph display. For those users who wish to compute the RL value independent of the front panel loss and mode launch loss we describe the process in some detail in the following subsections.

5.1 Adjusting RL for Variable IL

Any measurement of RL involves making a connection to the device under test. If there is loss in the connection, this loss will add directly to the apparent RL. As a practical matter, the insertion loss of the connector to the calibration artifact, component or network is not controllable and typically varies by several tenths of a dB every time a new connection is made. Since the OBR provides a means of measuring this connector loss, reproducible RL measurements are possible even in the presence of variable connector loss. The insertion loss is defined as a single pass loss but return loss is measured for light which travels both from the instrument to the reflection event and back. Therefore to make a RL measurement independent of the IL between the instrument and the reflection event, twice the value of the IL should be subtracted from the apparent RL value to arrive at the IL-independent RL value. The IL is measured from the difference in the Rayleigh back scatter levels between the fiber immediately before the front panel connection and the fiber immediately before the reflection event, as described in Section 4.

5.2 Adjusting RL for Scatter Level Shift

When the RL event is in MMF, the IL adjustment calculation is complicated by the fact that the Rayleigh scatter level for MMF and SMF is generally different, and the shift in scatter level must be accounted for to produce an accurate result. To properly measure insertion loss we need to know the relative difference in scatter levels. The simplest way to measure the difference is to fabricate and measure the IL of a jumper cable composed of Corning SMF-28E spliced to a segment of the multi-mode test fiber spliced back to SMF-28E, as depicted in Figure 19. In this example we used Corning InfiniCor 300), a 62.5 micron diameter core graded index MMF. The OBR upper graph trace of the jumper cable is shown in Figure 20.

Figure 19. Jumper required for measuring relative scatter level of multi-mode fiber.

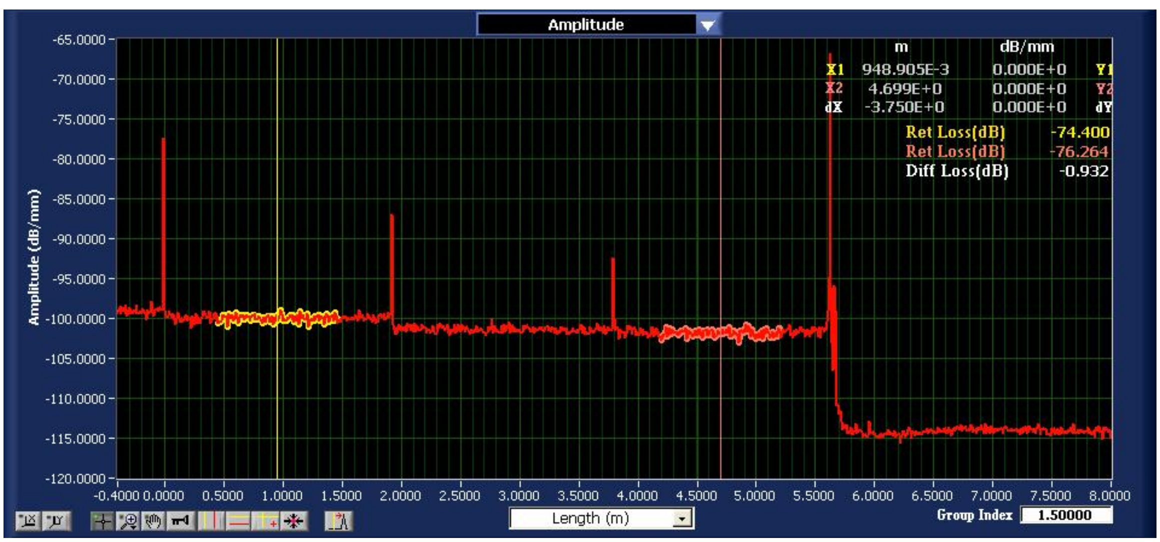


Figure 20. The OBR upper graph trace for the network depicted in Figure 19.

If we label the RL of each of the three sequential fiber segments as RL_a, Rl_b and RL_c, then the average IL of the splices is:

$$IL_{splice} = -\frac{1}{2}\left(\frac{RL_a - RL_B}{2} + \frac{RL_b - RL_c}{2}\right) = \left(RL_c - RL_a\right)/4 \tag{5}$$

The shift in scatter level Δ_{SL} between the multi-mode fiber and SMF-28 is given by the difference between the measured gap between RL_a and RL_b or between RL_b and RL_c and twice IL_{splice}:

$$\Delta_{SL} = -((RL_a - RL_b) + 2IL_{splice}) = (2IL_{splice} + (RL_b - RL_c)) = RL_b - \frac{(RL_a + RL_c)}{2} \tag{6}$$

For the case shown in Figure 20 IL_{splice} is -0.47 dB and Δ_{SL} is -0.53 dB at 1550 nm. The scatter level shift should be subtracted from scatter level separation when calculating IL when transitioning from SMF-28E to InfiniCor 300. Note that the Rayleigh back scatter level difference Δ_{SL} is likely to be dependent on the mode power distribution, so a different value is needed to compensate RL for IL when a mode scrambler is used.

5.3 RL Measurement Examples

We will demonstrate that reasonable RL values are obtained for several FC/PC and FC/APC connectors and for a FC/PC to FC/PC union in MMF with a direct launch from standard SMF-28E and InfiniCor 300 62.5 micron diameter core graded-index MMF.

The first three artifacts chosen to measure were FC/PC connectors because the RL value is straight forward to estimate for a flat end face reflector. The expected value of the RL can be calculated using the Fresnel equation at normal incidence:

$$RL = 10\log\left(\left(\frac{n-1}{n+1}\right)^2\right) \tag{7}$$

According to the fiber manufacturer the value for the effective index of refraction n for the multi-mode fiber used is 1.491 at 1300 nm, resulting in an expected RL of -14.11 dB. This result assumes pristine surface polish quality and cleanliness, a true 90 degree with respect to the fiber axis polish angle and that all modes will interact with the interface as if at normal incidence. Connector imperfections and the presence of higher order modes generally should serve to reduce the light returning to the instrument.

The upper graph trace of a multi-mode jumper with a FC/PC end connector is shown in Figure 21. In this case the high amplitude of the connector reflection required a reduction in the OBR detector gain from 24 dB to 12 dB to avoid detector saturation. The measured RL without correction for the front panel IL in this example was -16.446 dB.

IL is measured with best accuracy at the highest detector gain setting (24 dB) since at this gain setting the difference between the instrument noise level and the fiber scatter level is maximized. In order to increase the gain without saturating the detectors, another multi-mode jumper was attached to the jumper connection under test in order to reduce the connector back reflection. Reduction in the amplitude of the connector reflection also eliminates its contribution to the nearby fiber scatter level. The upper graph trace for both multi-mode jumper cables in series is shown in Figure 22. Although the addition of the second jumper reduces the RL amplitude of the FC/PC connector, the insertion loss at the front panel remains the same. The difference in scatter level between the fiber just inside the instrument and on the other side of the front panel connection is -1.614 dB. However, when calculating the front panel connection insertion loss we must remember to adjust for the difference in back scatter level inherent to the difference in fiber type that we calculated in the previous sub-section:

$$IL = -\,(1.614-0.530)\,/\,2 \;=\; -0.542 \text{ dB} \tag{8}$$

Thus the corrected value for RL is:

$$RL' = RL - 2IL = -16.446 - 2(-0.542) \text{ dB} = -15.362 \text{ dB} \tag{9}$$

The RL for the remaining two FC/PC connectors was calculated in an identical manner.

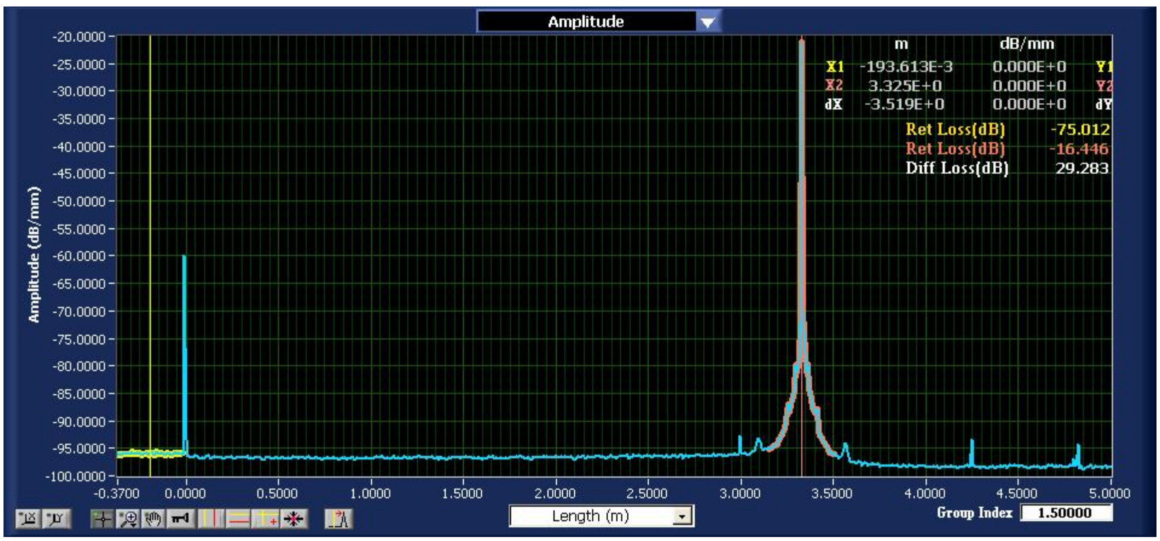


Figure 21. The OBR upper graph trace for a multi-mode jumper with a FC/PC end connector

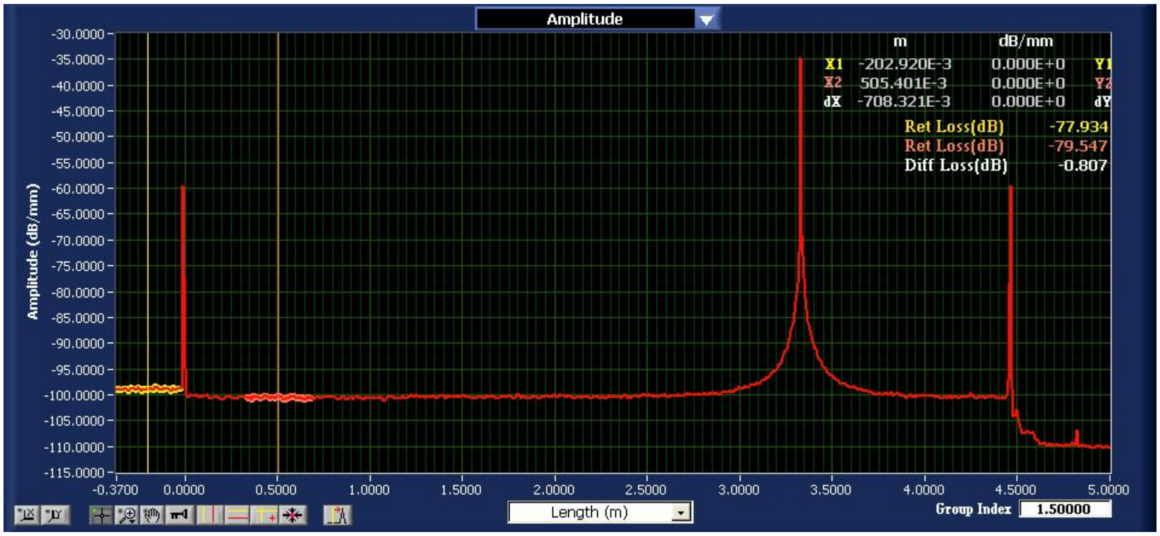


Figure 22. The OBR upper graph trace for jumper in Figure 21 with a second jumper added to reduce the reflection from the FC/PC connector so that the highest detector gain setting could be used for the IL measurement.

The RL of the FC/APC connector and the FC/PC union connection was measured and adjusted for IL at the front panel connection without the need for a second trace at a higher detector gain setting because the RL for these connectors was low enough that the detectors did not saturate even at the highest gain setting.

The RL results obtained for several FC/PC and FC/APC connectors and for a FC/PC to FC/PC union in 62.5 micron core graded-index multi-mode fiber are listed below in Table 3. Although the RL values for the FC/PC connectors were lower than in the ideal case described by Equation 7, the results are consistent with slight connector imperfections which generally reduce the back reflection. The RL value for the FC/PC to FC/PC connection is also typical for such a connection. The results for the FC/APC connectors also seem reasonable, since these connectors are designed to limit RL to -55 dB or below in single mode fiber, and our launch conditions should approximate single mode behavior. We would expect a much stronger reflection from these connectors if a mode converter was used to fully populate the available modes since the angled end face would tend to launch some higher order modes efficiently back into low order modes which would return to the instrument with low loss.

Table 3. RL results for a variety of reflective artifacts adjusted for IL at the front panel connection.

Event	Return Loss (dB) OBR without mode converter @ 1550 nm
FC/PC connector in MM fiber	-14.51
FC/PC connector in MM fiber (slightly scratched)	-15.28
FC/PC connector in MM fiber (slightly scratched)	-15.36
FC/PC to FC/PC connection in MM fiber	-28.89
FC/APC connector in MM fiber	-61.64
FC/APC connector in MM fiber	-60.00

6 Modal Dispersion Effects on Spatial Resolution

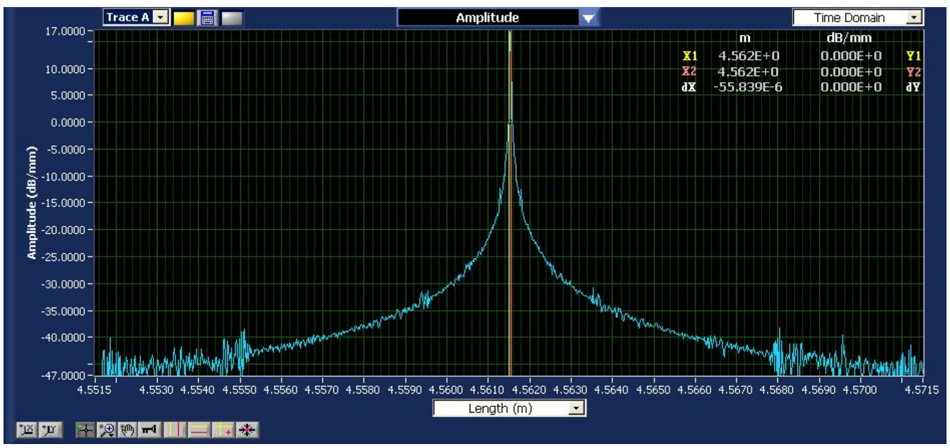
The presence of multiple modes inevitably degrades the spatial resolution with which the OBR can detect light returning from a singular reflection event because each mode will experience a different effective propagation index of refraction and thus experiences a slightly different path length from the instrument to the event and back. Even though the graded index core profile is designed to minimize the difference in effective path length between modes, modal dispersion is significantly higher than chromatic dispersion in single mode fiber for any practical length of fiber or communication channel wavelength span. For graded-index multi-mode fibers designed to operate at both 850 and 1300 nm the core index profile is nearly parabolic in profile and is generally designed to interact with material dispersion to give minimum pulse spreading near 1100 nm so that the dispersion limited bandwidth is roughly equal at the two operational wavelengths.[6] The solution for the time spread in the optical signal due to modal dispersion $\Delta\tau$ is exact in the case of a parabolic index profile:

$$\Delta\tau = \frac{n_1(n_1 - n_2)^2}{2c} L \qquad (10)$$

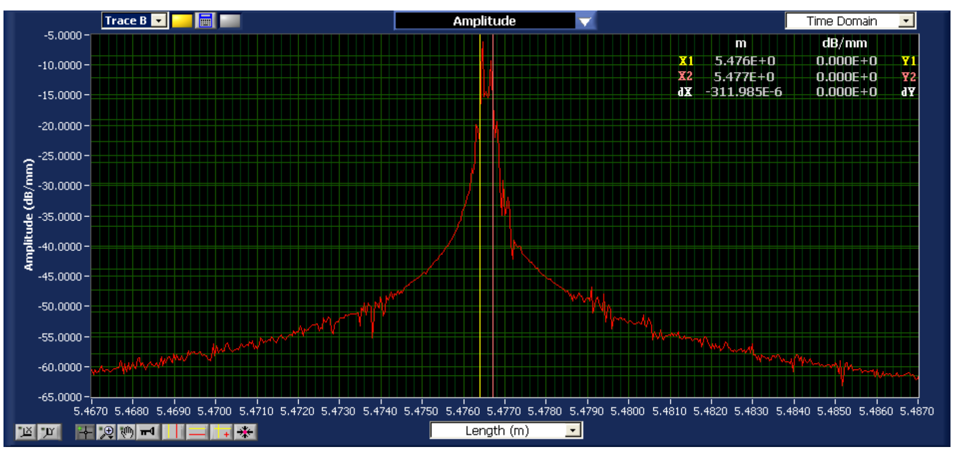
In the above equation L is the length of the multi-mode fiber segment and c is the speed of light in a vacuum. This equation gives a rough order of magnitude approximation for the resolution of a spatially resolved reflection event for a uniform mode power distribution and indicates that the spatial spreading of features increases linearly with the distance along the fiber. We expect that modal dispersion will be substantially reduced for the direct launch case since only a few low order modes are launched.

To demonstrate the effects of modal dispersion on spatial resolution of reflection events, we examined the high resolution OBR scans of three artifacts: a gold mirror in SMF, a cleaved fiber end face in MMF with a direct mode launch, and a FC/PC reflector in MMF using the mode scrambler to fully populate the fiber modes. The lower trace amplitude plots are shown in Figure 23. In all three cases the span of the vertical axis is 60 dB and the span of the horizontal axis is 20 mm. The peak width of the reflection events broadens dramatically as the mode population increases.

The width of each reflection event at 3 dB and 10 dB down from the peak amplitude is shown in Table 4. In the case of the gold mirror in single mode fiber the 3 dB full width is clearly less than the 40 micron sampling limit. Launching only a few low order modes by connecting the multi-mode fiber directly to single mode fiber increases the peak width, but these widths are still far below those of the full mode launch. Given an estimated value for (n_1-n_2) of 0.020, the peak width calculated from Equation 10 for the full mode launch case is 1.4 mm, a value which falls in between the 3 and 10 dB width measurements for the full launch case.



a)



b)

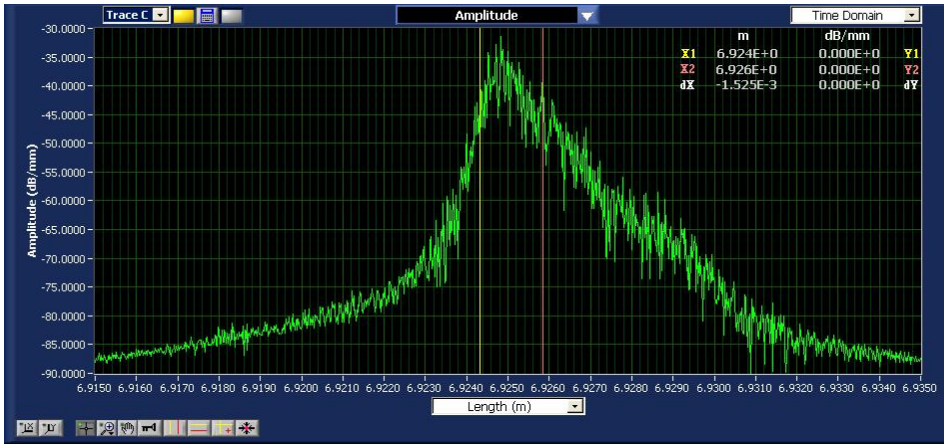
c) 

Figure 23. High resolution amplitude plots of a) a gold mirror in single mode fiber, b) a cleaved endface in multi-mode fiber with a direct single-mode to multi-mode launch which only populates a few low order modes, and c) a FC/PC connector in multi-mode fiber with a full mode launch using a mode converter. The yellow and red vertical cursors are placed 10 dB below the peak; in each case the x-axis spans 20 mm.

Table 4. Reflection peak width measurements for the three cases shown in Figure 23 showing the peak spreading effects of modal dispersion.

	Full Width at -3 dB (μm)	Full Width at -10 dB (μm)
SMF, Au mirror	<40	60
MMF, FC/PC reflector, SMF to MMF direct launch	230	310
MMF, FC/PC reflector, mode converter full launch	500	1530

Summary

The OBR is quite capable of making repeatable IL and RL measurements in multi-mode fiber with the same accuracy as for single mode fiber. However, consideration must be given to the mode launch conditions when interpreting results. We have investigated the OBR response under two easily repeatable mode launch conditions: a direct launch case in which single mode fiber is spliced directly to graded-index multi-mode fiber in which only a few low order modes are launched, and the fully populated case in which a mode scrambler is used to assure uniform mode power distribution. The mode launch condition should be chosen by the user to best suit their application requirements.

Both launch conditions have strengths when making IL measurements. Those made with the mode scrambler are more sensitive to loss mechanisms which predominantly affect high order modes, such as macro-bends, barrel or waist splices, or splices with cladding bubbles. IL measurements made using a direct single mode to multi-mode launch are more sensitive to loss events which also shift the mode power distribution, such as an offset splice. Similar rules of thumb apply for multi-mode cable connections: sensitivity to the defect depends on defect location with respect to the center of the core and propensity to scramble the mode population distribution. It is difficult to know in advance which measurement method will provide the surest method of detecting a problem splice or connection so there is some advantage to using both methods to search for network faults.   For all loss mechanisms detailed in this engineering note, the OBR IL results using a mode converter were within 0.2 dB of the results obtained from a commercial multi-mode power meter. Differences in the measurements are likely attributed to differences in the mode power distribution produced by the mode converter and the LED fiber coupled source of the power meter.

The OBR is capable of making RL measurements independent of variable IL using a direct launch from single-mode to multi-mode fiber. The RL results produced from FC/PC and FC/APC connectors were consistent with values expected for propagation in single mode fiber. The effects on the RL measurement of a fully populated mode launch are complicated by the difficulty in simultaneously measuring the loss associated with the mode converter and the difference in Rayleigh back scatter level between the single mode fiber in the instrument and the multi-mode fiber under test. Further guidance in interpreting RL results in the uniform mode power distribution case will be supplied in a later engineering note.

Finally, it is important to keep in mind that the spatial resolution of reflection events will necessarily suffer from modal dispersion. If resolving several closely spaced reflection events is of importance, best results will be obtained using a direct single mode to multi-mode fiber mode launch which only populates a few low order modes in the fiber under test, and by limiting the multi-mode fiber length to the reflection events as much as possible.

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Headquarters:	3157 State Street Blacksburg, VA 24060
Main Phone:	1.540.961.5190
Toll-Free Support:	1.866.586.2682
Fax:	1.540.961.5191
Email:	solutions@lunainc.com
Website:	www.lunainc.com

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