Return Loss Measurement in the Presence of Variable Insertion Loss Using Optical Frequency Domain Reflectometry

Stephen Kreger, Mark Froggatt, Dawn Gifford, Matthew Wolfe, and Brian Soller
Luna Technologies, 3157 State Street, Blacksburg, VA 24060

Abstract: The high spatial resolution and high sensitivity inherent to optical frequency domain reflectometery enables precise measurements of distributed insertion loss and return loss events. The ability to compensate return loss for variable insertion loss greatly adds to the accuracy and practicality of measurements. Further, the capability of measuring the Rayleigh backscatter internal to the instrument provides a stable power calibration artifact.

Introduction

Excessive system return loss (RL) negatively impacts source stability and contributes to loss in high-speed fiber optic telecommunication systems. In order to meet system performance goals, precise measurement of return loss in individual components as well as in installed networks is required, especially when temporary mechanical connections are used. Most current return loss measurements are made using optical continuous wave reflectometry (OCWR) and optical time domain reflectometry (OTDR) [1]. One of the primary error sources for RL measurements using these devices is the error induced by variable insertion loss at the connection to the test equipment optical interface. While this error source may be minimized by splicing the device under test (DUT) to the instrument, this procedure is not practical in high volume manufacturing environments or for installed networks.

Both OTDR and optical frequency domain reflectometery (OFDR) are well suited for characterizing networks with some degree of spatial resolution. Both techniques typically have enough sensitivity to monitor the fiber Rayleigh backscatter level which can, in turn, be used to measure distributed loss and gain [2,3]. Typically OTDRs lack sufficient spatial resolution to be useful at the component and module level where one might be interested in, for example, locating a spurious reflection among a concatenation of several components each with multiple elements. OFDR is a tunable laser-based frequency domain technique that has several distinct advantages over time domain and low coherence techniques when the optical systems under test are several tens of meters in length [4,5]. These advantages include sub-millimeter resolution measurements over a few hundred meters of optical length, high sensitivity, and high dynamic range.

The capability of measuring localized insertion loss using OFDR presents a unique opportunity to provide consistent measurements of device RL even in the presence of variable connector loss, even for short lead lengths. Further, the lack of a dead zone and high sensitivity allows our OFDR-based instrument to calibrate return power levels to the Rayleigh backscatter level of fiber within the instrument. This onboard calibration capability provides a highly stable and reproducible reference for RL measurements. This paper outlines the methodology used to establish a value for the scatter in optical fiber, and how this Rayleigh scatter level is used to maintain consistent reflection measurements.

Measurement Apparatus

The optical network used to implement OFDR is shown in Fig. 1. Light from a tunable laser source is split into measurement and reference optical paths. In the measurement path, the light is further split by a 50/50 coupler. A third coupler is used to recombine the light from the measurement path with the light from the reference path. After recombination, the light is split by a polarization beam splitter. Interference is detected at two PIN photodiodes that are connected via amplification circuitry to a data acquisition card. This polarization diverse detection scheme ensures that an interference signal will be present on at least one of the detectors irrespective of the polarization state of the field reflected from the device under test (DUT). Not shown in Fig. 1 is an auxiliary interferometer used to monitor phase error during laser tuning. This technique is called triggered acquisition and is commonly used in OFDR systems to remove laser tuning errors from the data [4]. Also not shown is a portion of the network wherein a Hydrogen Cyanide gas-cell is used to monitor the instantaneous wavelength of the scanning laser.

The network shown in Fig. 1 is used to measure reflected power as a function of wavelength. The back-reflected power as a function of length is obtained via the Fourier transform of the raw data (see reference [6] for details). The maximum measurable length for this instrument is determined by the sampling resolution in the optical

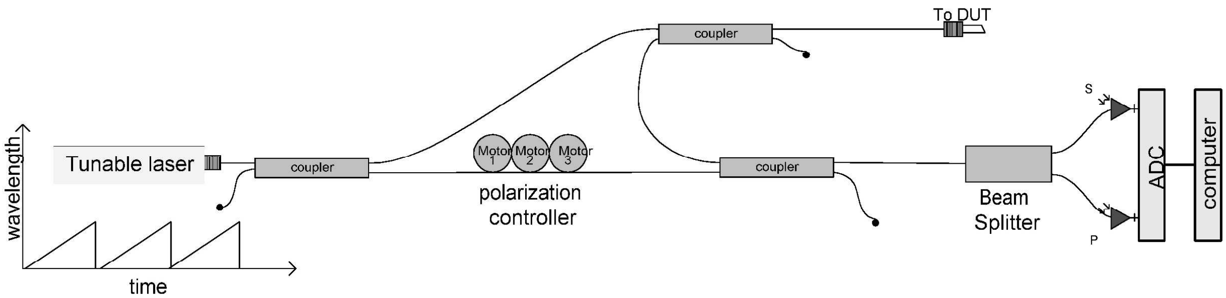

Fig. 1. Optical network used to perform polarization diverse measurements of Rayleigh backscatter.

frequency domain which is in turn determined by the physical delay difference of the auxiliary interferometer used for data triggering. In this paper, the instrument used had a maximum scan range of 30 m with ~20 µm spatial resolution.

To calibrate the measured back-reflection to an absolute RL, the response of a set of polished flat end face connectors was recorded. The expected value of the RL can be calculated using the Fresnel equation:

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

According to the fiber manufacturer the value for the effective index of refraction n for these connectors is 1.4682 at 1550 nm, resulting in an expected RL of 14.44 dB. Although the above equation is only an approximation and the RL of such connectors is dependent on the surface polish quality and cleanliness, we have observed that the consistency for such connectors manufactured in-house is better than that of most commercially available metal-film fiber reflectors. After the reference set of reflectors was used to scale the return power, the Rayleigh backscatter level for a segment of fiber within the instrument close to the front panel connector was recorded. Upon any subsequent recalibration of the instrument, any drift in detector responsivity or amplifier gain can be corrected for by comparing the measured backscatter level of the fiber segment to the recorded value. Although we have not yet completed an extensive survey, we have found that the repeatability of the Rayleigh backscatter level for the fiber used in our instruments, Corning SMF-28e, is excellent, with a standard deviation less than 0.05 dB for a 1 m integration width.

Making Insertion Loss-Independent Return Loss Measurements

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 OFDR provides a means of measuring this connector loss, reproducible RL measurements are possible even in the presence of variable connector loss.

To demonstrate the repeatability of a RL measurement in the presence of loss, we measured the RL of a polished ST connector at the end of a 1.9 m lead with a FC-APC connection to the measurement instrument. To induce a varying amount of loss, the fiber was mandrel wrapped at roughly 0.3 m after the connection to the instrument. Fig. 2 shows two example scans of this DUT and one scan with no device connected. Because the ST connector has a high RL, two measurements are required to determine the RL. First, the DUT is measured with no alteration. Second, a measurement is taken with the fiber immediately before the ST connector pinched off to reduce the RL from the connector. This reduces the effect of the tails from the reflection peak on the measured data and, thus, enables a measurement of the Rayleigh scatter immediately before the reflection.

Four measurements of the reflected power along the measured traces are required to determine the RL with best accuracy. These measurements are obtained by measuring the integrated normalized power over a defined length centered at a specified location. The first power measurement, P_0, is recorded over a span of fiber inside the instrument and will be the sum of the Rayleigh back scatter P_{RA} and the background noise level P_B. The second power measurement P_1 is recorded over a span of fiber just prior to the reflection event and is given by the sum of P_B and the Rayleigh backscatter level divided by the double pass attenuation factor A. This factor, A, is the

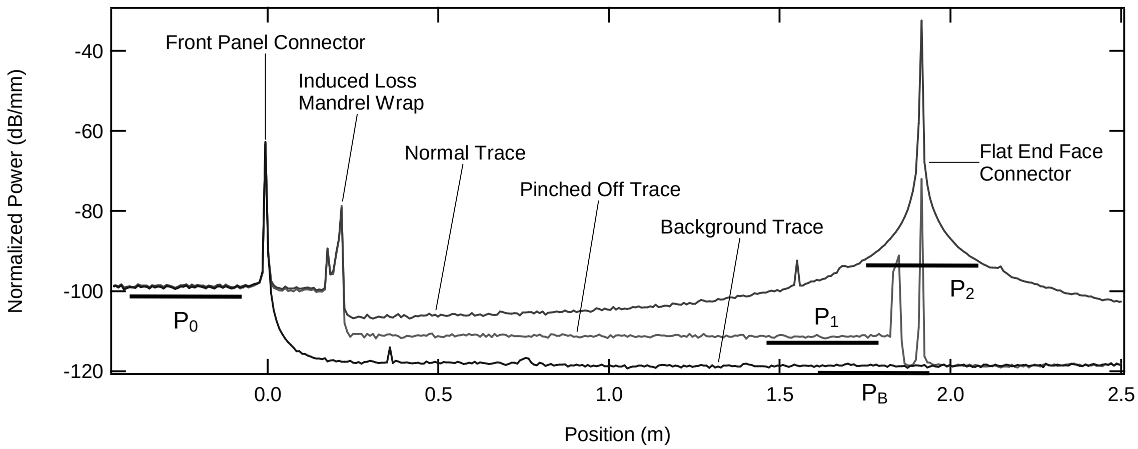

Fig. 2. Sample traces for determining the return loss of a reflection event in the presence of high insertion loss. The four dark lines beneath the traces indicate measurement integration regions for the four measurements.

attenuation caused by the double-pass insertion loss (from the front panel connection and the mandrel-wrap) between P_0 and P_1. Both P_0 and P_1 are measured using the pinched-off trace. If the attenuation is large, it is also necessary to record a value of the background noise level, P_B, by placing measuring the power in the background trace near the locations where P_1 and P_2 are recorded. The expressions describing P_0 and P_1 are,

$$P_0 = P_{RA} + P_B \tag{2}$$

and

$$P_1 = P_{RA} / A + P_B \, . \tag{3}$$

The power returned from the reflection event P_2 is recorded using the unaltered trace over a span of data centered on the reflection event. In addition to the power from the ST reflection P_{ST}, this measurement will also contain components due to P_{RA} and P_B. P_2 is, then, expressed as:

$$P_2 = \left(P_{ST} + P_{RA} \big/ 2 \right) / A + P_B \tag{4}$$

Using these equations, the IL of the loss events and the RL of the ST connector can be calculated as

$$IL = 10 \log(A) / 2 = 5 \log\left(\frac{P_0 - P_B}{P_1 - P_B} \right) \tag{5}$$

and

$$RL = -10 \log(P_{ST}) = -10 \log\left(\frac{P_0 - P_B}{P_1 - P_B} (P_2 - P_B) - (P_0 - P_B)/2 \right). \tag{6}$$

To demonstrate that the return loss value is repeatable even with high insertion loss, the RL was calculated for the ST connector described above with varying numbers of wraps around a mandrel. The recorded reflection traces without the pinch off applied for each attenuation level are shown in Fig. 3. The results of the measurements are shown in Table 1. The resulting standard deviation for the RL calculation over a range of insertion losses from 0.79 to 14.65 dB was only 0.05 dB.

To demonstrate the repeatability between instruments, RL measurements were taken on a set of seven carefully polished flat end face connectors using four different instruments. The insertion loss at the front panel connection for these measurements was generally less than 0.5 dB. The results are presented in Table 2. The standard deviation is a measure of the combined variations of the RL measurement and the instrument calibration procedure and is equal to or less than 0.15 dB.

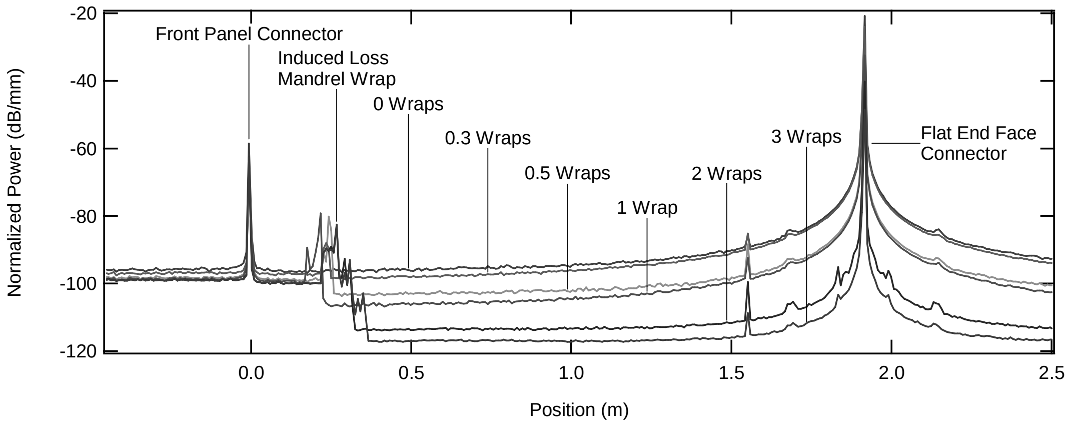

Fig. 3. Traces of a reflection event with varying amounts of insertion loss.

Table 1. Return Loss measurements for the same component for a wide range of Insertion Loss.

	Relative Power Level Measurements				Results	
Mandrel Wraps	P_0 (dB)	P_1 (dB)	P_2 (dB)	P_B (dB)	Insertion Loss (dB)	Return Loss (dB)
0	-76.45	-78.01	-16.09	-96.31	0.79	14.51
0.3	-76.43	-81.20	-19.42	-96.31	2.43	14.57
0.5	-76.44	-84.88	-23.19	-96.31	4.36	14.47
1	-76.41	-88.82	-27.76	-96.21	6.62	14.52
2	-76.48	-93.74	-35.29	-96.31	10.36	14.57
3	-76.48	-95.85	-43.91	-96.31	14.65	14.61

Table 2. Return loss values for a set of flat end face connectors for 4 different instruments.

	Return Loss (dB)						
Instrument	Con 1	Con 2	Con 3	Con 4	Con 5	Con 6	Con 7
OBR 7022	14.21	14.19	14.19	14.37	14.10	14.82	14.36
OBR 7071	14.35	14.39	14.48	14.63	14.45	14.97	14.69
OBR 7078	14.37	14.31	14.30	14.56	14.23	15.01	14.59
OBR 7083	14.55	14.46	14.44	14.70	14.37	15.10	14.66
Std. Dev.	0.14	0.12	0.13	0.14	0.15	0.12	0.15

Summary

We have demonstrated that an OFDR-based instrument is capable of producing repeatable RL measurements even for wildly different values of the insertion loss in close proximity to the reflection event. This capability greatly adds to the utility of the measurement, as the uncertainty due to the insertion loss at the connection to the instrument is eliminated. Additionally, we have shown that our instrument calibration procedure, which ties the RL values for a reference set of flat end face fiber reflectors to the Rayleigh backscatter level for a fiber segment inside the instrument, produces consistent results between instruments. Establishing the consistency of the precise level of the fiber Rayleigh scatter for fiber manufactured under very tight tolerances may eventually allow its use as a widely available, inexpensive, and stable return loss calibration artifact. These are preliminary results and are expected to improve as we continue to refine the calibration process for absolute return-loss measurement.

References

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