INSERTION-LOSS MEASUREMENT ACCURACY FOR FIBER-OPTIC COMPONENTS – AN ANALYSIS

Christopher T. Allen
Ralph D. Taylor
James R. Stone

DIT-MCO International

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CHRISTOPHER T. ALLEN
Associate Professor
The University of Kansas
2335 Irving Hill Road
Lawrence, KS 66045
callen@eecs.ku.edu
785-864-3017

RALPH D. TAYLOR
Director of Engineering
DIT-MCO International
5612 Brighton Terrace
Kansas City, MO 64130
Taylor.Ralph@ditmco.com
816-444-1111

JAMES R. STONE
Program Manager
DIT-MCO International
5612 Brighton Terrace
Kansas City, MO 64130
jstone@ditmco.com
816-444-1111

Abstract –

This paper attempts to provide an answer to the question: To what accuracy can insertion-loss measurements be made on low-loss, multi-mode fiber-optic cables, patch cords, and modules having a variety of terminations? To answer this question, and to provide insight regarding the factors that dominate the measurement accuracy, a thorough analysis of the measurement process is required. Relevant terminology is defined for purposes of this analysis to minimize confusion. In addition, to limit the discussion to those factors affecting the question at hand, a list of underlying assumptions is provided.

An analysis of a measurement system using custom-built power measurement hardware showed an overall insertion-loss measurement accuracy ranging from ± 0.18 to ± 0.32 dB, depending on the measurement system configuration and the calibration procedure. Two separate factors contribute to the overall accuracy: an instrument measurement accuracy of about ± 0.092 dB, and a calibration accuracy which ranges from ± 0.15 dB to ± 0.30 dB. The analysis included the effects of two connector types having maximum (manufacturer specified) insertion losses of ± 0.25 to ± 0.30 dB. While power measurement factors (such as wavelength variability, amplifier gain variability, receiver nonlinearity, and finite A/D converter resolution) contribute to the overall measurement accuracy, calibration uncertainty due to connector loss variability dominates the overall measurement accuracy and can be two to three times larger than these factors.

An analysis of a measurement system composed of commercial optical power measurement equipment, fiber-optic switches, and LED sources showed an overall insertion-loss measurement accuracy ranging from ± 0.33 to ± 0.59 dB, depending on the measurement system configuration, the calibration procedure, and power meter measurement accuracy. The instrument measurement accuracy ranged from about ± 0.13 dB to ± 0.35 dB, depending on the power meter. The calibration accuracy again ranged from ± 0.15 to ± 0.30 dB, as the same connector types were used in this analysis, as before. For systems using the more accurate (± 0.10 dB) power measurement equipment, the overall accuracy was dominated by the connector loss variability. However for systems using the less accurate (± 0.25 dB) power measurement equipment the overall insertion-loss measurement accuracy was dominated by the power measurement system accuracy.

Introduction

Well made multi-mode fiber-optic cables, patch cords, and modules may have very little insertion loss. Testing of these fiber-optic components for compliance with specifications requires very accurate insertion-loss measurement capabilities. For example, to reliably measure the insertion loss of a fiber-optic patch cord with an expected insertion loss of 0.2 dB, a measurement system accuracy of less than ± 0.1 dB may be desired. A question important to this process is 'To what accuracy can insertion-loss measurements be made on low-loss, multi-mode fiber-optic cables, patch cords, and modules having a variety terminations?' To properly answer this question, the insertion-loss measurement process must be carefully analyzed, all possible error sources must be identified, and the nature and magnitude of the errors must be determined. In this report, the various error sources that degrade the insertion-loss measurement accuracy are identified and estimates made regarding their magnitudes. To minimize confusion, relevant terminology is defined for purposes of this analysis. In addition, to limit the discussion to those factors affecting the question at hand, a list of underlying assumptions is provided.

Executive Summary

Well made multi-mode fiber-optic cables, patch cords, and modules may have very little insertion loss. Testing of these fiber-optic components for compliance with specifications requires very accurate insertion-loss measurement capabilities. For example, to reliably measure the insertion loss of a fiber-optic patch cord with an expected insertion loss of 0.2 dB, a measurement system accuracy of less than ± 0.1 dB may be desired. A question important to this process is 'To what accuracy can insertion-loss measurements be made on low-loss, multi-mode fiber-optic cables, patch cords, and modules having a variety terminations?' To properly answer this question, the insertion-loss measurement process must be carefully analyzed, all possible error sources must be identified, and the nature and magnitude of the errors must be determined. In this report, the various error sources that degrade the insertion-loss measurement accuracy are identified and estimates made regarding their magnitudes.

The major sources of error include optical power measurement accuracy and system calibration accuracy. Factors affecting the power measurement accuracy include inaccurate knowledge of the optical wavelength, electronic amplifier stability, nonlinear characteristics of the measurement system, and quantization errors introduced during analog-to-digital conversion. Factors affecting calibration accuracy include imperfect knowledge of the insertion loss through a reference patch-cord used as a calibration standard, insertion-loss variations due to changing the modal distributions of the optical signal within the optical fiber, and variability of the insertion loss through the fiber-optic connectors. A mathematical model of the measurement process was defined so that the uncertainties associated with these error sources could be combined. In this analysis, error sources were generally modeled with Gaussian (or normal) probability distributions. Manufacturer's specified maximum and minimum limits were used to determine the spread of the Gaussian bell-shaped curve. The standard deviation (σ) was determined such that 6σ was the difference between the upper limit and the lower limit of the relevant parameter. Following standard error analysis techniques, if these error sources are behaving independently then the overall measurement accuracy is found by taking the square root of the sum of the squares of the various uncertainties. Based on this approach, accuracy relates to a $\pm 3\sigma$ limit on the measurement error; therefore the probability of the measurement error exceeding the stated accuracy is 0.0026.

Following this approach, different measurement system configurations using various measurement subsystems and system calibration schemes were considered to assess their effects on the overall measurement accuracy. Analysis of these various measurement systems provided overall insertion-loss measurement accuracies that ranged from about ± 0.18 dB to ± 0.59 dB. In most cases the factor dominating the overall measurement accuracy was found to be the uncertainty in the loss through a mated pair of fiber-optic connectors. This factor alone accounts for ± 0.13 to ± 0.15 dB of measurement uncertainty. A secondary source of measurement uncertainty was errors in the measurement instrumentation which ranged from ± 0.092 to ± 0.35 dB. Only situations where the instrumentation accuracy was comparable to or worse than the calibration accuracy, did the instrumentation accuracy dominate the resultant overall measurement accuracy. As power measurement equipment with measurement accuracies better than ± 0.1 dB are commercially available, it is clear that the factor limiting routine insertion-loss measurements with accuracies of ± 0.1 dB is the uncertainty associated with the connector losses.

While many factors contribute to the insertion loss through fiber-optic connectors, the dominant cause is the mechanical misalignment of the two cores of fibers being mated. Precise core alignment is impossible due to the various mechanical tolerance issues. To aid the system designer, manufacturers typically specify the maximum loss through a mated pair of their connectors. While the typical loss is less than this maximum, it represents an upper limit. The uncertainty introduced by the inclusion of various combinations of mated connector pairs during calibration and device testing is the key factor limiting insertion-loss measurement accuracy.

1 Introduction

The purpose of this document is to provide an answer to the question: To what accuracy can insertion-loss measurements be made on low-loss multi-mode fiber-optic cables, patch cords, and modules having a variety terminations? To answer this question, and to provide insight regarding the factors that dominate the measurement accuracy, a thorough analysis of the measurement process is required. To minimize confusion, relevant terminology is defined for purposes of this analysis. In addition, to limit the discussion to those factors affecting the question at hand, a list of underlying assumptions is provided.

2 Definitions

accuracy: The degree of conformity of a measured or calculated value to its actual or specified value. [1]
Accuracy is how close to the actual value you are. For example, if the number you are representing is 4 and you say it's 3, you are inaccurate by 1. [2]

bias: 1. A systematic deviation of a value from a reference value. 2. The amount by which the average of a set of values departs from a reference value. [1]

central limit theorem: Whenever a random sample of size n is taken from any distribution with mean μ and variance σ^2, then the sample mean x will be approximately normally distributed with mean μ and variance σ^2/n. The larger the value of the sample size n, the better the approximation to the normal. [5]

error: The difference between a computed, estimated, or measured value and the true, specified, or theoretically correct value. [1]

insertion loss: 1. The loss resulting from the insertion of a device in a transmission line, expressed as the reciprocal of the ratio of the signal power delivered to that part of the line following the device to the signal power delivered to that same part before insertion. Note: Insertion loss is usually expressed in dB. 2. In an optical fiber system, the total optical power loss caused by insertion of an optical component, such as a connector, splice, or coupler. [1]

precision: 1. The degree of mutual agreement among a series of individual measurements, values, or results; often, but not necessarily, expressed by the standard deviation.
2. With respect to a set of independent devices of the same design, the ability of these devices to produce the same value or result, given the same input conditions and operating in the same environment. 3. With respect to a single device, put into operation repeatedly without adjustments, the ability to produce the same value or result, given the same input conditions and operating in the same environment. [1]
Precision is how well you define a value. For example, if the value you are representing is 4.321 and you say it's 4.3, you are precise to two places. Numerically, precision is the amount of decimal digits that you are capable of measuring. [2]

resolution: 1. The minimum difference between two discrete values that can be distinguished by a measuring device. Note: High resolution does not necessarily imply high accuracy. 2. The degree of precision to which a quantity can be measured or determined. 3. A measurement of the smallest detail that can be distinguished by a sensor system under specific conditions. [1]

random errors: These errors can be evaluated on the basis of repetitive measurements of the same measurement. In insertion-loss measurements, typical random errors are: changes of the power level and the non-reproducibility of the connector loss. Averaging may be advisable if these errors are too large. [3]

systematic errors: Errors that remain constant in repetitive measurements. These errors can usually only be estimated. In insertion-loss measurements, the main source of systematic errors usually are: errors due to changing the connector type, nonlinearity caused by the difference in power levels, changes of the wavelength and uncontrolled fiber modes. An indication of the magnitude of the systematic errors can be obtained by demounting and reconstructing the measurement setup and taking a new measurement; this should be done several times over several days. [3]

uncertainty: A range that is likely to contain the true value of the parameter being measured. [4]

A graphical illustration of these concepts is shown in Fig. 2.1. Here a parameter x is measured (x_{MEAS}) which differs from the true value of x (x_{TRUE}). The magnitude of this difference ($|x_{TRUE} - x_{MEAS}|$) is the **error**. From a study of the statistical nature of the error its probability distribution (f(x)) can be described by the Gaussian distribution, described by its mean (μ) and standard deviation (σ). The probability of the error being smaller than 3σ is 99.74%, hence the range $\mu \pm 3\sigma$ is called the 99.76% confidence interval. Therefore by defining the **uncertainty** to be $\Delta x = 3\sigma$, the probability of the true value being within the interval $x_{MEAS} \pm \Delta x$ is 99.76%. Since in most cases the true value of the parameter of interest is unknown, it is often not possible to directly determine the accuracy of a measurement. Therefore the **uncertainty** is used to predict the **accuracy** of the measurement system. Hence a small uncertainty signifies a small measurement error and, therefore, a more accurate measurement.

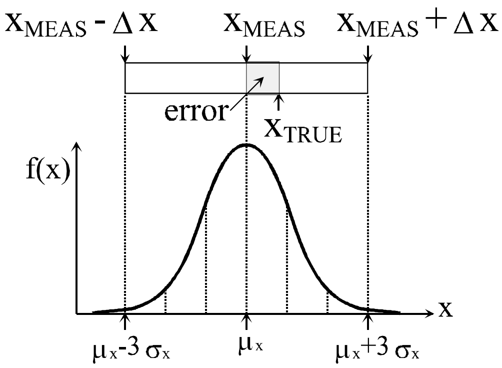

Figure 2.1 Illustration relating a measured value ($x_{MEAS} = \mu$) to the true value (x_{TRUE}), the error ($|x_{TRUE} - x_{MEAS}|$), the uncertainty ($\Delta x = 3\ \sigma$), and the confidence interval ($x_{MEAS} - \Delta x \rightarrow x_{MEAS} + \Delta x$) assuming the probability distribution of x (f(x)) follows a Gaussian or normal distribution.

3 Assumptions

The following assumptions have been made regarding this analysis. While many diverse factors affect fiber-optic signal transport, for the special case of multimode fibers illuminated by light-emitting diodes (LEDs) some of these factors can be ignored.

3.1 Ignoring optical interference

Multiple reflections within a fiber-optic channel can result in interference between the direct and reflected signals. Destructive and constructive interference can occur, depending on the relative phases of the direct and reflected signals. This interference is usually unpredictable and can corrupt optical power measurements. Fortunately, illumination from LEDs is naturally very broad in spectral extent. Consequently, the optical signal may be considered to be incoherent having a very short coherence length. It is therefore reasonable to assume that multiple reflections within the optical channel will be incoherent in nature effectively eliminating optical interference effects. This assumption is not valid if narrowband sources (like lasers) are used.

3.2 Ignoring polarization-dependent loss

Some fiber-optic systems (cables, connectors, modules, etc.) exhibit polarization-dependent loss wherein the insertion loss through the system varies with the polarization of the illumination. This phenomenon can corrupt insertion-loss measurements. However light from an LED is inherently unpolarized, meaning that all possible polarization states are uniformly generated. As a result, the effects of system polarization-dependent losses are avoided and consistent insertion-loss measurements are possible. This assumption is not valid if polarized sources (such as lasers) are used.

3.3 Ignoring photodiode spillover

As light emitted from the fiber end impinges on the photodiode, photons falling beyond the active area of the photodiode do not contribute to the power measurement. A large area photodiode is assumed for this application such that the active area of the photodiode is understood to be larger than the projected spot size from the optical fiber. Under this assumption, detection inefficiencies due to spillover are ignored.

4 Insertion-loss formulas

4.1 Direct measurement

Insertion loss (IL) is defined as the ratio of the transmitted optical power to the received or detected optical power,

$$IL = \frac{P_{TX}}{P_{RX}} \tag{4.1}$$

Fig. 4.1 illustrates this principle.

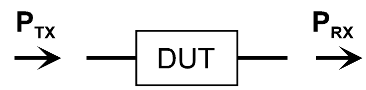

Figure 4.1 Relationship of transmitted power (P_{TX}) and detected power (P_{RX}) to the device under test (DUT).

When defined in this manner, an insertion of loss of 2 means that ½ of the transmitted power was detected at the receiver. An insertion loss of 10 means that 10% of the transmitted power was detected at the receiver.

It is often useful to express the insertion loss in a logarithmic scale such as decibels,

$$IL\,(dB) = 10 \cdot \log_{10}(P_{TX}) - 10 \cdot \log_{10}(P_{RX}) \tag{4.2}$$

So when expressed in dB, the insertion loss of 2 becomes 3 dB and the insertion loss of 10 becomes 10 dB.

Transmitter power and receiver power can be expressed individually in dBm (decibels relative to 1 mW) as P_{TX}(dBm) and P_{RX}(dBm) so that this expression simplifies to

$$IL(dB) = P_{TX}(dBm) - P_{RX}(dBm) \tag{4.3}$$

In only the simplest test configuration will only these two measurements be sufficient to make an accurate insertion-loss measurement. In a more common situation, losses in the measurement setup must be taken into account so that the insertion loss of just the device under test (DUT) is reported. To remove the inherent losses in the test setup, a calibration measurement is performed to determine a calibration factor, K'_{CAL}. Hence, the equation describing how insertion loss is determined now becomes

$$IL = \frac{P_{TX}}{P_{RX}} K'_{CAL} \tag{4.4}$$

as expressed in linear units or expressed in logarithmic units as

$$\mathrm{IL\ (dB)} = P_{TX}\mathrm{(dBm)} - P_{RX}\mathrm{(dBm)} + K'_{CAL}\mathrm{(dB)} \qquad (4.5)$$

The accuracy to which the DUT's insertion loss is measured depends on how accurately we know each of these three terms.

4.2 Inferred measurement of transmit power

In some measurement configurations, it is impractical to disconnect the transmit connection to measure P_{TX} and then reconnect it to the DUT for the insertion-loss measurement. In these cases rather than measuring the transmitted power directly, a sample of the transmitted power is continuously output for measurement, as illustrated in Fig. 4.2.

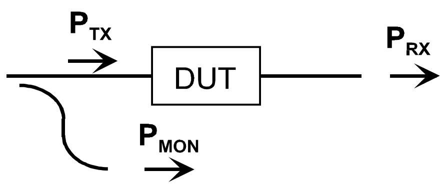

Figure 4.2 Relationship of transmitted power (P_{TX}), monitored power (P_{MON}), and detected power (P_{RX}) to the device under test (DUT).

In these instances, insertion loss is obtained from the two output powers, P_{RX} and P_{MON}. While a precise knowledge of the how P_{MON} relates to P_{TX} is necessary to apply the formulas presented previously, the need for this knowledge can be avoided through a calibration process. In a calibration measurement, a reference device with a known insertion loss (IL_{REF}) replaces the DUT. Measured values for P_{RX} and P_{MON} are made for an arbitrary (non-zero) P_{TX} value. From this data a calibration constant is obtained.

$$K_{CAL} = \frac{P_{RX}}{P_{MON}} IL_{REF} \qquad (4.6)$$

or expressed in decibels

$$K_{CAL}\ \mathrm{(dB)} = P_{RX}\mathrm{(dBm)} - P_{MON}\mathrm{(dBm)} + IL_{REF}\mathrm{(dB)} \quad (4.7)$$

When the DUT is introduced into the measurement system and measured values for P_{RX} and P_{MON} are obtained, the insertion loss of the DUT can then be determined,

$$IL_{DUT} = \frac{P_{MON}}{P_{RX}} K_{CAL} \qquad (4.8)$$

or expressed in decibels

$$IL_{DUT}\ \mathrm{(dB)} = P_{MON}\mathrm{(dBm)} - P_{RX}\mathrm{(dBm)} + K_{CAL}\mathrm{(dB)} \quad (4.9)$$

5 Accuracy, Errors, and Uncertainties

Accurate insertion-loss measurements require accurate measurements of the transmitted power (or its surrogate, P_{MON}), the received power, and an accurate calibration term representing measurement setup losses. [Note that for purposes of measuring the insertion loss, relative power measurement is sufficient when an external calibration of the measurement system is used. Therefore for this application, accurate power measurement refers to repeatability and stability and not to absolute power measurement accuracy.] For each of these terms, deviation of the measured value from its true value represents an error. By estimating the magnitude of various errors, an uncertainty of the measurement can be estimated; where the uncertainty represents bounds on the range likely to contain the true value. Our knowledge of the uncertainty in each of these terms contributes to the overall uncertainty of our knowledge of the insertion-loss measurement.

Based on statistics, each uncertainty term can be modeled by a probability distribution that represents its characteristics. While the most common statistical model applied is the well known Gaussian or normal distribution (see Fig. 2.1) which is defined by a mean (μ) and standard deviation (σ), other models may be used when appropriate. Regardless of which models are used to describe the individual error components, the Gaussian distribution best describes the probability of the overall insertion-loss uncertainty due to the combination of the numerous independent random processes (the central limit theorem).

In modeling the errors with the Gaussian distribution, the uncertainty associated with a particular power measurement is usually expressed as $P \pm \Delta P$, where ΔP denotes the uncertainty. This uncertainty represents a 3σ deviation from the mean such that the probability that true value will deviate from the estimate (P) by more than the uncertainty (ΔP) is 0.26 %.

To obtain the overall accuracy for the insertion-loss measurement, the individual uncertainties, or errors, must be combined. Fortunately it is reasonable to assume that the uncertainties in each of these terms are independent (i.e., uncorrelated), as this simplifies the process of combining these various factors. Basic error analysis theory states that when the various error parameters are combined through multiplication or division, as is the case here, then the overall accuracy (or error) is simply the root-sum-square (RSS) of the fractional uncertainty of each of the constituent error terms,

$$\frac{\Delta IL}{IL} = \sqrt{\left(\frac{\Delta P_{MON}}{P_{MON}}\right)^2 + \left(\frac{\Delta P_{RX}}{P_{RX}}\right)^2 + \left(\frac{\Delta K_{CAL}}{K_{CAL}}\right)^2} \qquad (5.1)$$

Since the error terms are effectively normalized by the underlying value, to express the overall uncertainty in decibels, we simply take the RSS of each error term expressed in decibels,

$$\Delta \text{IL (dB)} = \sqrt{\Delta P_{MON}^2(\text{dB}) + \Delta P_{RX}^2(\text{dB}) + \Delta K_{CAL}^2(\text{dB})} \quad (5.2)$$

Several error sources must be considered to evaluate the accuracy of the insertion-loss measurement. A thorough analysis requires a detailed knowledge of the measurement system, the key components involved, and the behavior of each key component. Fundamental to insertion-loss measurements are the measurement of optical power (P_{RX} and P_{MON}) and determination of calibration factors (K_{CAL}). Detailed analyses of these error sources are presented separately. If similar hardware is typically used for both power measurements (P_{RX} and P_{MON}), the uncertainties associated with P_{RX} and P_{MON} will be comparable.

Instrumentation accuracy, defined here as the accuracy of the measurement system ignoring external factors such as connector effects and calibration issues, is found by combining two power measurement uncertainties.

$$\Delta P_{INS}(\text{dB}) = \sqrt{\Delta P_{RX}^2(\text{dB}) + \Delta P_{MON}^2(\text{dB})} \quad (5.3)$$

With the instrument accuracy (ΔP_{INS}) and the calibration accuracy (ΔK_{CAL}), the overall insertion-loss measurement accuracy is found by combining them in a root-sum-square process

$$\Delta \text{IL (dB)} = \sqrt{\Delta P_{INS}^2(\text{dB}) + \Delta K_{CAL}^2(\text{dB})} \quad (5.4)$$

5.1 Power measurement analysis

In the measurement of the optical power, a reverse-biased photodiode is used convert the incident light (photons) to an electrical current, as illustrated in Fig. 5.1. This current may be converted into a voltage with a series resistor. An amplifier having gain G may be used to boost the signal level prior to the analog-to-digital (A/D) converter where the signal is then digitized with N bits of resolution.

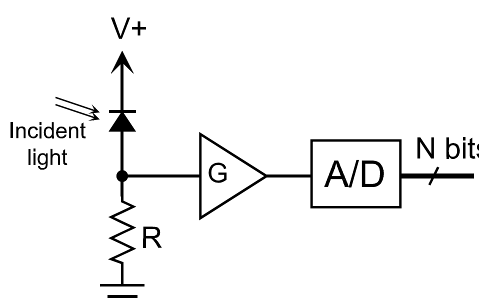

Figure 5.1 Block diagram of the optical power measurement subsystem.

5.1.1 Effects of wavelength variation

The relationship between incident optical power and resulting electrical current in a reverse-biased photodiode is characterized by its responsivity ($\Re$),

$$I = \Re\, P \quad (5.5)$$

which has units of A/W. Interaction of the photons with the semiconductor material in the photodiode determines the wavelength dependence of the responsivity, $\Re(\lambda)$. Assuming the operating wavelength is well below the cutoff wavelength of the semiconductor material, the responsivity is proportional to the wavelength

$$\Re(\lambda) \sim \lambda \quad (5.6)$$

such that

$$\Delta P_\lambda = P_{true} \frac{\Delta\lambda}{\lambda} \quad (5.7)$$

where ΔP_λ is the uncertainty associated with wavelength variation ($\Delta\lambda$) about the nominal wavelength (λ) and P_{true} is the true optical power level. Stated another way, if the central wavelength changes by 1 % the responsivity will also change by 1 % and, consequently, the resulting electrical current and optical power estimate will change by 1 % (0.04 dB).

5.1.2 Effects of temperature variation

While responsivity is temperature independent, total electrical current through the photodiode is temperature dependent. Total photodiode current, I_T, includes the optically induced current (described above) and a 'dark current' due to leakage through the reverse-biased diode.

$$I_T = I_s\,(e^{\frac{Vq}{nkT}} - 1) + \Re P \quad (5.8)$$

The dark current is the first term to the right of the equal sign. Here q is the magnitude of electronic charge (1.602×10^{-19} C), k is Boltzmann's constant (1.38×10^{-23} J/K), n is a device dependent constant between 1 and 2, I_S is the saturation current (typically on the order of pA to fA), and T is the absolute temperature (expressed in Kelvin). Since the photodiode is operated in reverse bias mode, the bias voltage, V, is negative and the exponential evaluates to a value much less than one. Consequently, while dark current is temperature dependent, its overall effect is typically negligible compared to the photocurrent (typically µA to mA).

5.1.3 Effects of noise

Temperature also plays a role in another error source, electrical noise. The signal from the photodiode will always be accompanied by additive electrical noise. Photodiode noise is composed of two noise phenomena – thermal noise and shot noise. For cases of modest optical incident power (µW range), thermal noise is the dominant of the two noise types. Both noise types are characterized by a random voltage (or current) with a Gaussian probability distribution, having a zero mean value and a standard deviation related to the noise power. The spectral distribution of this noise is uniform (frequency independent) and very broadband. For thermal noise, also called Johnson noise, the noise power is proportional to the absolute temperature and the system bandwidth, so that the uncertainty in the measured optical power due to thermal noise is

$$\Delta P_{THERMAL} = \sqrt{4\,k\,T\,B} \tag{5.9}$$

where k is Boltzmann's constant, T is the absolute temperature, and B is the system bandwidth (expressed in Hz). It is often convenient to express the thermal noise power in photodiodes in terms of its 'noise equivalent power' (NEP) which has units of W/√Hz. The NEP represents the equivalent incident optical power level that will result in a unity signal-to-noise ratio. The noise power is proportional to NEP squared so that the uncertainty in the measured optical power due to NEP is

$$\Delta P_{NEP} = NEP\,\sqrt{B} \tag{5.10}$$

In addition to thermal noise, another noise phenomenon, shot noise, must be considered. Shot noise power is proportional to the total diode current, hence the uncertainty in the measured optical power due to shot noise is

$$\Delta P_{SHOT} = \sqrt{2\,q\,B\,(\Re\,P + I_{DARK})} \tag{5.11}$$

Since the electrical noise is additive (i.e., primarily independent of P_{TRUE}), the overall uncertainty in the measured optical power due to measurement noise is found by combining these factors in an RSS fashion,

$$\Delta P'_{NOISE} = \sqrt{\Delta P_{NEP}^2 + \Delta P_{SHOT}^2} \tag{5.12}$$

Scaling this factor by the true optical signal power produces a multiplicative factor representing the effects of noise on the measurement uncertainty,

$$\Delta P_{NOISE} = \frac{\sqrt{\Delta P_{NEP}^2 + \Delta P_{SHOT}^2}}{P_{TRUE}} \tag{5.13}$$

Note that despite the temperature dependent nature of this noise source, for narrowband applications (where the system bandwidth is small) this noise term is usually quite small compared to the signal and should not be a dominant factor in the overall measurement uncertainty.

5.1.4 Effects of electronic amplifier gain variation

Often the photodiode is followed by an electronic amplifier to boost the level of the detected signal. While this amplifier will also introduce additional noise to the measurement, the more serious concern is uncompensated amplifier gain variations which will also contribute to uncertainty in the measured optical power. The uncertainty associated with gain variations (ΔP_{GAIN}) are proportional to the true optical power (P_{TRUE}) being measured, as

$$\Delta P_{GAIN} = P_{TRUE}\,\frac{\Delta G}{G} \tag{5.14}$$

where G is the nominal gain and ΔG is the gain variation. So for a nominal voltage gain of 10 and a gain variation of ± 0.1 (± 0.08 dB), the uncertainty due to gain variations is ± 1 % (or ± 0.04 dB).

5.1.5 Effects of finite A/D resolution

An analog-to-digital converter with N bits of resolution is used to digitize the analog current or voltage signal representing the optical signal power. The number of possible output states (dynamic range) in this case is 2^N. Due to the limited (finite) resolution of the A/D converter, no information is provided on signal level variations below the smallest quantization level (the least-significant bit or LSB). Therefore the conversion accuracy is limited by the rounding process used to obtain the LSB of the digital output. The resultant uncertainty of this process is ± ½ of an LSB. The relative effect of this uncertainty depends on the value being digitized. Assuming the true power level is within the dynamic range of the A/D converter, i.e., P_{TRUE} is less than the full-scale power level (P_{FS}), the uncertainty in the power measurement due to the A/D uncertainty of ± ½LSB is

$$\Delta P_{A/D} = \frac{\mathrm{round}\left(\frac{P_{TRUE}}{P_{FS}}\,2^N\right) + 0.5}{\mathrm{round}\left(\frac{P_{TRUE}}{P_{FS}}\,2^N\right)}, \quad \text{for } P_{TRUE} \le P_{FS} \tag{5.15}$$

where round(·) rounds the argument to the nearest integer value. Note that the measurement uncertainty increases for decreasing power values where progressively smaller portions of the A/D converter's dynamic range are used.

5.1.6 Effects of measurement nonlinearities

Ideally the entire measurement process is linear, i.e., the measured power is proportional to the true power over a wide range of values. For this to be true, each process involved in the measurement must be linear including the photodiode conversion, the amplifier transfer function, the A/D conversion, and any other operations in the measurement system. Nonlinearities in the overall transfer function will produce errors and add to measurement uncertainty. While complete component models may describe nonlinear characteristics, this aspect is often not specified. In these cases typical values which range from ± 0.003 (± 0.015 dB) to ± 0.01 (± 0.05 dB), may be used.

5.1.7 Power measurement accuracy

Combining all of these factors yields an overall power measurement (P_{MEAS}),

$$P_{MEAS} = \mathrm{round}\left(\frac{(P_{TRUE} + P'_{NOISE})\,\Re\,G}{P_{FS}}\right) \tag{5.16}$$

To quantify the accuracy of the power measurement (ΔP_{MEAS}), the fractional uncertainty of each of the error factors in this process is combined in an RSS fashion. As before, this can also be accomplished by finding the RSS of the individual uncertainties expressed in decibels,

$$\Delta P_{MEAS}(dB) = \sqrt{\begin{aligned}&\Delta P_{\lambda}^2(dB) + \Delta P_{NOISE}^2(dB) + \\ &\Delta P_{GAIN}^2(dB) + \Delta P_{A/D}^2(dB) + \\ &\Delta P_{NONLINEAR}^2(dB)\end{aligned}} \qquad (5.17)$$

5.1.8 Instrument accuracy

Since determination of the DUT's insertion loss requires two power measurements (P_{RX} and P_{MON}), and identical power measurement hardware systems are used, the instrument accuracy will be

$$\begin{aligned}\Delta P_{INS}(dB) &= \sqrt{\begin{aligned}&2\,[\Delta P_{\lambda}^2(dB) + \Delta P_{NOISE}^2(dB) + \\ &\Delta P_{GAIN}^2(dB) + \Delta P_{A/D}^2(dB) + \\ &\Delta P_{NONLINEAR}^2(dB)]\end{aligned}} \\ &= \sqrt{2}\cdot\Delta P_{MEAS}(dB)\end{aligned} \qquad (5.18)$$

5.2 Calibration analysis

Calibration of the measurement system is required to correct for any systematic errors and to remove the effects of any measurement bias. Uncertainties associated with the determination of the calibration factor (K_{CAL}) will contribute to the calibration accuracy (ΔK_{CAL}) which is a factor in determining the insertion-loss measurement accuracy (ΔIL). To determine calibration accuracy, the calibration process is presented and analyzed. As a starting point, a simplified representation of a typical insertion-loss measurement setup is shown in Fig. 5.2.

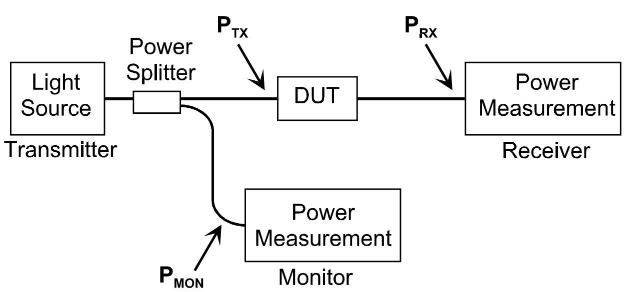

Figure 5.2 Insertion-loss measurement configuration with continuous power monitoring.

To determine P_{TX} from the measured P_{MON}, as shown in Fig. 5.2, requires knowledge of the splitting ratio of the power splitter and losses through the cables that are not part of the DUT. Rather than accurately measure each of these unknowns (with measurement uncertainties), an alternative is to calibrate the entire measurement system using a reference device with a known insertion loss. Not shown in this simple example are the fiber-optic connectors. Insertion loss through mated connector pairs plays a significant role in calibration accuracy. In addition, configuration of the measurement system will affect the calibration procedure. Three different measurement configurations illustrating how this may be accomplished are shown later in this section. In all three examples, the DUT has fiber pigtails with connector terminations. In the first two examples, the DUT connectors are of the same type as the measurement setup. In the third example the DUT connectors are different from one another as well as those of the measurement setup requiring the use of adapter cables.

5.2.1 Connector loss uncertainty

Insertion loss through a fiber-optic connector depends on several parameters. These include dissimilarities between the parameters of the fibers being terminated (such as mismatches in the numerical apertures and core diameters), and imperfect mechanical alignment of the fiber cores in the termination (such as angular misalignment, longitudinal separation, and lateral displacement) [6]. Assuming the fibers being joined are essentially identical, the dominant factor affecting connector insertion loss is misalignment of the fiber core due to lateral displacement (also called axial displacement). Factors contributing to core lateral displacement include noncircularity of the fiber core and cladding as well as that of the ferrule and its bore; diameter tolerances of the fiber core and cladding as well as of the ferrule diameter and bore; concentricity of the fiber core/cladding and the ferrule/bore.

For a step-index fiber, the insertion loss (coupling efficiency) is proportional to the common-core area overlap between the two fiber end faces [7].

$$IL_{CONN} = \frac{2}{\pi}\cos^{-1}\left(\frac{d}{2a}\right) - \frac{d}{2\pi}\sqrt{1-\left(\frac{d}{2a}\right)^2} \qquad (5.19)$$

Here d is the lateral displacement and a is the core radius. For small displacements relative to the core radius, d « a, insertion loss (expressed in decibels) is linearly related to the displacement.

$$IL_{CONN}(dB) = 2.8\ d/a \qquad (5.20)$$

Combining all of the factors contributing to the overall lateral displacement yields a Gaussian probability distribution for this parameter. The connector insertion loss can also be modeled with a Gaussian distribution. To determine model parameters for this distribution (i.e., μ and σ), manufacturer's specifications are perhaps the best source. By selecting the mean value to be half of the maximum and the standard deviation to be one-sixth of the maximum, the selection the worst case (μ+3σ) loss would be the maximum and the best case (μ-3σ) would be 0 dB. For example, if the manufacturer specifies a 0.3 dB maximum connector loss, the mean insertion loss (μ) would be 0.15 dB and the standard deviation (σ) of 0.05 dB will yield a worst case (μ+3σ) loss of 0.3 dB and a best case (μ-3σ) loss of 0 dB. Figure 5.3 shows the assumed insertion-loss distribution for a connector with a manufacturer's specified maximum loss of 0.3 dB.

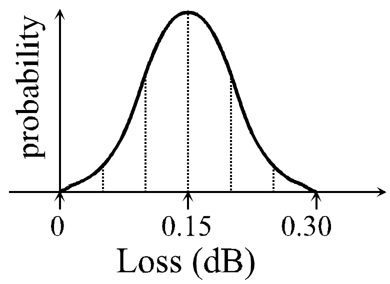

Figure 5.3 Assumed probability distribution for a connector with a maximum specified loss of 0.3 dB.

While a fully excited multimode fiber carries numerous propagation modes, as the signal passes through a fiber-optic connector, the modal distribution may be changed. Specifically, if higher order modes are excited, as these non-sustainable modes propagate, signal power is lost resulting in a reduced power at the receiver. If the modal distribution of the input signal is restricted (fewer modes launched into the connector), the loss due to modal perturbation in the connector may be reduced. Consequently, connector insertion loss may be somewhat dependent on the mode distribution of the input signal. Based on previous studies [8], the maximum insertion loss due to modal variations may be as high as 0.03 dB, so that the uncertainty due to this affect (ΔIL_{MODAL}) would be $\pm$ 0.015 dB. Since this connector induced loss due to modal distribution variation would occur only once per passage of the signal through a series of connectors, it will only be counted once regardless of the number of connectors in the path.

5.2.2 Calibration with one lead-in fiber

In Fig. 5.4 (following the analysis of [9]) the DUT's connectors are of the same type as the measurement setup and the output fiber pigtail is of sufficient length to connect directly to the power measurement block labeled 'receiver.' In the first step of this measurement, the measurement setup is calibrated as shown in Fig. 5.4(a). In this configuration P_{MON} is the power measured in block labeled 'monitor' and the power measured in the block labeled 'receiver' represents both P_{TX} and P_{RX}. In this configuration, no calibration reference is used, hence the reference insertion loss is one (0 dB). The ratio P_{RX} to P_{MON} becomes the calibration constant, K_{CAL} as in (4.6).

The DUT is then added to the setup, as shown in Fig. 5.4(b), and new values for P_{RX} to P_{MON} are measured. The insertion loss of the DUT is then found using (4.8). Complicating this simple view is the additional loss introduced at the new connection pair into the setup. While the substitution of connector CY for C3 into the receiver should not change the power measurement results, loss through the C3/CX connector pair represents a new variable.

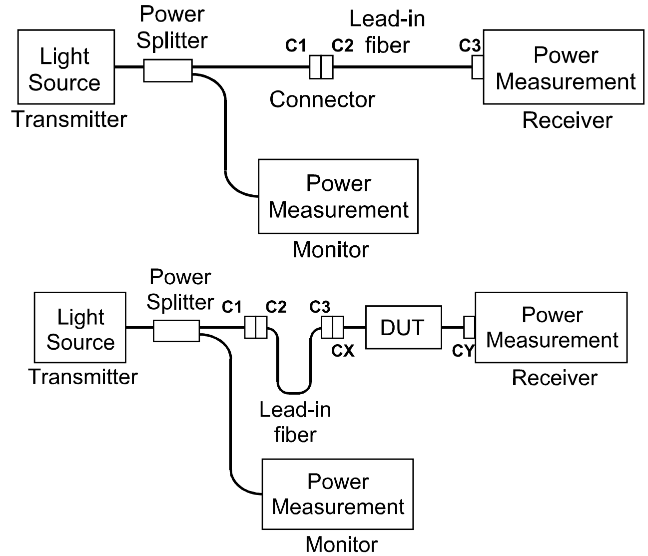

Figure 5.4 Conventional insertion-loss measurement process, (top) setup calibration, (bottom) measurement of DUT (after [9]).

Due to the inclusion of an additional connector pair in the DUT measurement setup compared to the calibration setup, the calibration constant (K_{CAL}) must be decreased by the mean insertion loss of one connector, including insertion loss due to modal distribution variation.

$$\begin{aligned} K_{CAL}\ (dB) = P_{RX}(dBm) - P_{MON}(dBm) - \\ (IL_{CONN}(dB) + IL_{MODAL}(dB)) \end{aligned} \tag{5.21}$$

Further, the insertion-loss uncertainty associated with this calibration procedure (ΔK_{CAL}) will be the same as the uncertainty due to one fiber-optic connector.

$$\Delta K_{CAL}(dB) = \sqrt{\Delta IL^2_{CONN}(dB) + \Delta IL^2_{MODAL}(dB)} \tag{5.22}$$

5.2.3 Calibration with two lead-in fibers

When the fiber pigtailed leads cannot be directly input to the power measurement system, a more complicated calibration results. Figure 5.5 illustrates this situation. Two lead-in fibers (with same-type terminations, C1/C2) are first connected for calibration, as before. The introduction of the DUT into the measurement system changes the connector configuration. Connector pair C1/C2 is replaced by C1/CX and CY/C2. Therefore the insertion loss of C1/C2 is removed and the insertion losses of two new connections are introduced to the measurement.

Due to the inclusion of an additional connector pair in the DUT measurement setup compared to the calibration setup, the calibration constant (K_{CAL}) must be decreased by the mean insertion loss of one connector, including insertion loss due to modal distribution variation.

$$\begin{aligned} K_{CAL}\ (dB) = P_{RX}(dBm) - P_{MON}(dBm) - \\ (IL_{CONN}(dB) + IL_{MODAL}(dB)) \end{aligned} \tag{5.23}$$

Further, since two new connector pairs are included in the DUT measurement compared to the calibration setup, and one previously existing connector pair is removed, the insertion-loss uncertainty associated with this calibration procedure (ΔK_{CAL}) will be roughly 70% greater than the uncertainty of the previous case, since

$$\Delta K_{CAL}(\mathrm{dB}) = \sqrt{\begin{array}{l}\Delta IL^2_{CONN}(\mathrm{dB}) + \Delta IL^2_{CONN}(\mathrm{dB}) + \\ \Delta IL^2_{CONN}(\mathrm{dB}) + \Delta IL^2_{MODAL}(\mathrm{dB})\end{array}} \quad (5.24)$$

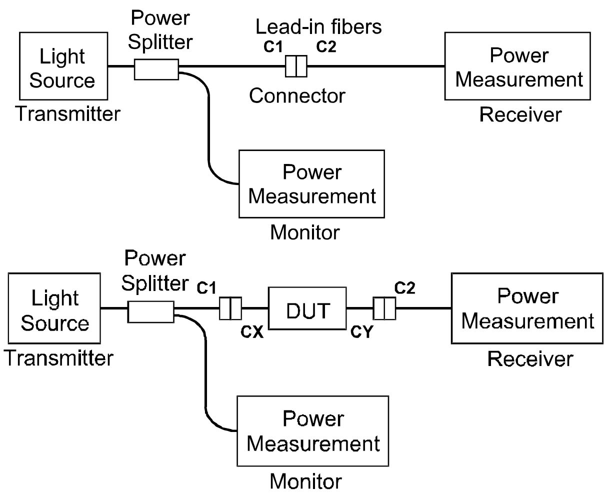

Figure 5.5 Conventional insertion-loss measurement process, (top) setup calibration, (bottom) measurement of DUT (after [9]).

5.2.4 Calibration with adapter cables

When the fiber terminations on the DUT's fiber pigtails are not compatible with those of the measurement setup, adapter cables are required. Further, if the DUT's two fiber terminations are dissimilar, an intervening reference cable must be used for calibration since the two adapter cables cannot be mated directly. This situation is illustrated in Fig. 5.6.

Under this scenario, several uncertainties are introduced into the calibration term, K_{CAL}. First, the system must be calibrated with a reference cable having the appropriate terminations. If the insertion loss through the reference cable is known with no uncertainty, then absolute insertion-loss measurements can be made. However if the absolute insertion loss through the reference cable is not known, the subsequent insertion-loss measurements will be relative to this standard.

Second, the measurement setup where the DUT replaces the reference cable does not include the effects of two connector pairs (C3/C4 and C5/C6) plus it now has the effects of two new connector pairs (C3/CX and CY/C6).

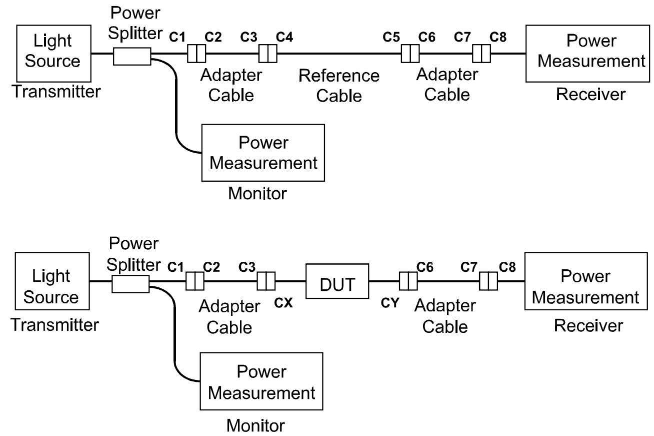

Figure 5.6 Insertion-loss measurement process for dissimilar connector types, (top) setup calibration, (bottom) measurement of DUT.

As the mean insertion loss of the two new connector pairs should be the same as that of the two connector pairs present during calibration, the only modification to the calibration constant (K_{CAL}) is reduction by the mean insertion loss due to modal distribution variation, if it is known.

$$K_{CAL}\ (\mathrm{dB}) = P_{RX}(\mathrm{dBm}) - P_{MON}(\mathrm{dBm}) - IL_{MODAL}(\mathrm{dB}) \quad (5.25)$$

Further, since two new connector pairs are included in the DUT measurement compared to the calibration setup, two previously existing connector pairs are removed, and the insertion loss of the reference cable has uncertainty, the insertion-loss uncertainty associated with this calibration procedure (ΔK_{CAL}) will be

$$\Delta K_{CAL}(\mathrm{dB}) = \sqrt{\begin{array}{l}2\,\Delta IL^2_{CONN1}(\mathrm{dB}) + 2\,\Delta IL^2_{CONN2}(\mathrm{dB}) + \\ \Delta IL^2_{REF}(\mathrm{dB}) + \Delta IL^2_{MODAL}(\mathrm{dB})\end{array}} \quad (5.26)$$

where ΔIL_{CONN1} and ΔIL_{CONN2} are the insertion-loss uncertainties of the two connector types.

5.3 Overall insertion-loss accuracy

Once the accuracy of the instrument and calibration are determined, they can be combined (Fig. 5.7) to obtain the overall insertion-loss measurement accuracy (Δ IL).

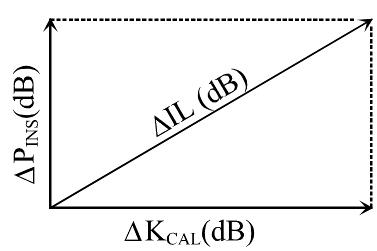

Figure 5.7 Combining calibration accuracy (ΔK_{CAL}) with instrument accuracy (ΔP_{INS}) to determine the overall insertion-loss accuracy (ΔIL).

Table 6.1 Measurement system parameters

Parameter	Symbol	Units	Nominal value	Minimum	Maximum
Wavelength	λ	nm	810	800	820
Number of bits in A/D	N	bits	16	--	--
Transmit power	P_{TX}	dBm	-18	--	-15
Receiver power	P_{RX}	dBm	-18	-40	-15
Monitor power	P_{MON}	dBm	-18	-40	-15
Amplifier gain	G	V/V	10	9.9	10.1
Temperature	T	° C	22	17	27
System bandwidth	B	Hz	1000	--	--
NEP	NEP	pW/√Hz	1	--	--
Dark current	I_{DARK}	NA	1	--	--
Responsivity	$\Re$	A/W	1	--	--
Full scale equiv. power into A/D	P_{FS}	dBm	-12	--	--
Receiver nonlinearity	$\Delta P_{NONLINEAR}$	dB	± 0.01	--	--
Reference cable IL uncertainty	ΔIL_{REF}	dB	± 0.05	--	--
Loss due to modal variation	IL_{MODAL}	dB	0.015	0	0.03
Connector loss (type 1)	IL_{CONN1}	dB	0.15	0	0.30
Connector loss (type 2)	IL_{CONN2}	dB	0.13	0	0.25

Due to the nature of the RSS process (5.4), if either term (ΔP_{INS} or ΔK_{CAL}) is significantly larger than the other, it will dominate the resulting overall accuracy (ΔIL).

6 Application to example measurement systems

Examples will be used to illustrate the application of the theory developed above to realizable measurement systems. Insertion-loss accuracy can be thought of as the combination of the accuracies of two separate and independent factors – instrument accuracy and calibration accuracy. In the first example a custom-built system is analyzed based on component parameters to determine the instrument accuracy, followed by a separate analysis focusing on the calibration accuracy. Finally, these factors are combined to determine the overall accuracy of the insertion-loss measurement. In the second example a measurement system assembled of commercial test equipment is similarly analyzed.

6.1 Example 1: Custom-built measurement system

6.1.1 Instrument accuracy

Table 6.1 lists the relevant system parameters.

From these parameters, the accuracy of the power measurement can be determined based on variations in the individual parameters. For example, the uncertainty due to thermal noise (characterized by the NEP) is found by

$$\Delta P_{NEP}(\mathrm{dB}) = 10\log_{10}\left(1+\frac{\mathrm{NEP}\sqrt{\mathrm{B}}}{P_{true}}\right) \tag{6.1}$$

$$\Delta P_{NEP}(\mathrm{dB}) = 10\log_{10}\left(1+\frac{1\times10^{-12}\sqrt{1000}}{10^{-4.8}}\right) \tag{6.2}$$

$$= \pm 0.00001\ \mathrm{dB}$$

From this analysis, summarized in Table 6.2, we find the overall accuracy of the relative power measurement is approximately ± 0.065 dB and the uncertainty factors dominating this accuracy are the wavelength variations and the amplifier gain variations. Note that noise effects (both NEP and shot) are inconsequential, so the effect of temperature variations will be negligible. To further improve relative power measurement accuracy, wavelength variations could be monitored so that this effect is eliminated. This would result in a power measurement accuracy of ± 0.041 dB. If, in addition to accurate wavelength knowledge, knowledge of the gain were improved so that this effect could be eliminated, the resulting power measurement accuracy would be reduced to ± 0.01 dB, that is the accuracy due to nonlinear receiver behavior.

Table 6.2 Power measurement uncertainties

Uncertainty due to …	Symbol	Units	Value
variations in wavelength	ΔP_{λ}	dB	± 0.05
NEP noise (P_{true} = -20 dBm)	ΔP_{NEP}	dB	± 0.00001
shot noise (P_{true} = -20 dBm)	ΔP_{SHOT}	dB	± 0.00002
noise (P_{true} = -20 dBm)	ΔP_{NOISE}	dB	± 0.00003
variations in amplifier gain	ΔP_{GAIN}	dB	± 0.04
finite A/D resolution (P_{true} = -20 dBm)	$\Delta P_{A/D}$	dB	± 0.0002
nonlinearities	$\Delta P_{NONLINEAR}$	dB	± 0.01
Total power measurement accuracy	ΔP_{MEAS}	dB	± 0.065

Table 6.3 Calibration uncertainties

Uncertainty in system with …	Symbol	Units	Value
one lead-in fiber (type 1 connector)	ΔK_{CAL}	dB	± 0.15
two lead-in fibers (type 1 connectors)	ΔK_{CAL}	dB	± 0.26
adapter cables (type 1 & 2 connectors)	ΔK_{CAL}	dB	± 0.28
adapter cables (type 1 connectors only)	ΔK_{CAL}	dB	± 0.30

Table 6.4 Insertion-loss measurement accuracies for custom-built measurement system

Insertion-loss measurement accuracy in systems with …	Symbol	Units	Value
one lead-in fiber (type 1 connector)	ΔIL	dB	± 0.18
two lead-in fibers (type 1 connectors)	ΔIL	dB	± 0.28
adapter cables (type 1 & 2 connectors)	ΔIL	dB	± 0.30
adapter cables (type 1 connectors only)	ΔIL	dB	± 0.32

Returning to the overall accuracy in power measurement of ± 0.065 dB, the uncertainty due to limited A/D resolution plays a minor role. In order for the overall accuracy to be dominated by this factor, the true signal power would need to be approximately –45 dBm, or some 27 dB below the transmitted power (ignoring the 20 dB amplifier gain).

As two power measurements are required for an insertion-loss measurement, the instrumentation accuracy is found by combining two power measurement uncertainties using (5.3). Therefore the instrumentation accuracy is ± 0.092 dB.

6.1.2 Calibration accuracy

Factors affecting calibration accuracy will vary with the measurement setup. Calibration accuracies for the various measurement setups described in sections under 5.2 are summarized in Table 6.3. In each case, the calibration accuracy is essentially the connector insertion-loss uncertainty scaled by the number of changed connections in the measurement setup. As these values are clearly much larger than the power measurement accuracy, any effort aimed at improving the insertion-loss measurement accuracy (reducing the measurement uncertainty) should focus on reducing the connector loss variability.

6.1.3 Overall insertion-loss measurement accuracy

The overall insertion-loss measurement accuracy is the root-sum-square of the instrumentation accuracy and the calibration accuracy. As expected, the overall insertion-loss measurement accuracy for all measurement system configurations (summarized in Table 6.4) is dominated by the calibration uncertainty. Based on these results, insertion-loss measurements will have an accuracy ranging from about ± 0.2 dB to ± 0.3 dB, due almost entirely to the variability in insertion loss through the fiber-optic

Table 6.5 Breakdown of the insertion-loss measurement accuracy factors for the case involving adapter cables with dissimilar connector types (types 1 and 2)

Uncertainty due to …	Symbol	Units	Value	% of Total
variations in wavelength	ΔP_{λ}	dB	± 0.071	5.7
noise (P_{true} = -20 dBm)	ΔP_{NOISE}	dB	± 0.000042	0.0
variations in amplifier gain	ΔP_{GAIN}	dB	± 0.057	3.7
finite A/D resolution (P_{true} = -20 dBm)	$\Delta P_{A/D}$	dB	± 0.00028	0.0
receiver nonlinearities	$\Delta P_{NONLINEAR}$	dB	± 0.014	0.2
system calibration factor	ΔK_{CAL}	dB	± 0.28	90.4
Total insertion-loss measurement accuracy	ΔIL	dB	± 0.30	100

Table 6.5 Breakdown of the insertion-loss measurement accuracy factors for the case involving adapter cables with a common connector type (type 1)

Uncertainty due to …	Symbol	Units	Value	% of Total
variations in wavelength	ΔP_{λ}	dB	± 0.071	4.9
noise (P_{true} = -20 dBm)	ΔP_{NOISE}	dB	± 0.000042	0.0
variations in amplifier gain	ΔP_{GAIN}	dB	± 0.057	3.2
finite A/D resolution (P_{true} = -20 dBm)	$\Delta P_{A/D}$	dB	± 0.00028	0.0
receiver nonlinearities	$\Delta P_{NONLINEAR}$	dB	± 0.014	0.2
system calibration factor	ΔK_{CAL}	dB	± 0.30	91.7
Total insertion-loss measurement accuracy	ΔIL	dB	± 0.32	100

connectors. Note that the addition of adapter cables, needed to accommodate dissimilar connector types, increases only slightly the uncertainty over the two lead-in fiber setup.

To provide insight regarding the significance of the various factors, a breakdown of the relative factors contributing to the overall insertion-loss accuracy is presented below for the case of the measurement setups using adapter cables. In Table 6.5 the case with dissimilar connector types (type 1 and 2) is addressed, while in Table 6.6 the case with common connector types (type 1) is addressed. In each analysis is also presented the relative contribution of each factor toward the total, based on its percent of the total sum-of-squares. In both cases the system calibration factor accounts for more than 90 % of the accuracy.

6.2 Example 2: Rack-and-stack measurement system

In this example a measurement system composed of commercially available test equipment (the rack-and-stack approach) is analyzed using the manufacturer's specifications. The same connectors used in the previous example are used in this analysis—therefore the calibration accuracy is the same as in the previous example.

6.2.1 Instrument accuracy

Figure 6.1 shows a configuration that uses one light source (LED), two power meters, and two optical switches to facilitate automatic testing of multiple channels. With this arrangement, the optical signal may be input to and output from any DUT ports. For each port of the DUT, a 2×2 optical coupler is used as a power splitter to provide a sample to the transmit power for monitoring. An optical power combiner is used to connect all of the monitor output signals from each power splitter to a commong monitor power meter is needed. Adapter cables are included to accommodate dissimilar DUT connector types.

Table 6.7 lists several commercially available power meters and their relevant parameters. For consistency, only equipment with operating wavelengths that include 810 nm were selected. Also, when applicable, performance values with operating temperatures including 22 to 27 ° C are included.

A review of the data shown in Table 6.7 reveals the typical accuracy (uncertainty) ranges from about ± 0.09 dB to

± 0.25 dB. Note that in some cases the value specified is the absolute power measurement accuracy, whereas the insertion-loss measurement, as described previously, requires only relative power measurement (assuming external calibration of the measurement system). Therefore, this data may underestimate the performance of commercially available power meters in insertion-loss measurement systems as the relative power measurement accuracy may be smaller.

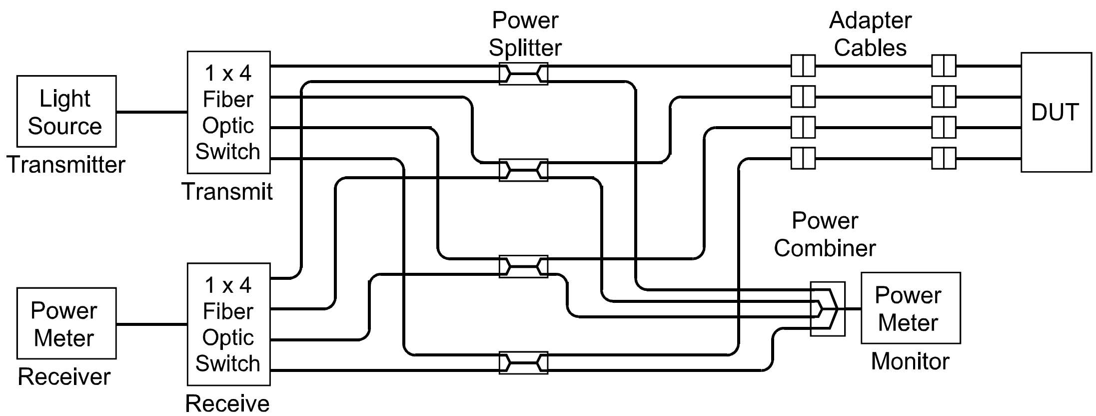

Figure 6.1 Block diagram of the rack-and-stack measurement system.

Table 6.7 Parameters of various commercially available power meters

Manufacturer **Model**	**Wavelength range (nm)**	**Power range (dBm)**	**Resolution[1] (dB)**	**Nonlinearity[2] (dB)**	**Accuracy[2,3] (dB)**
Agilent 81533B/81520A	450 to 1020	-100 to +10	0.001	0.04	± 0.095
Agilent 81530A	450 to 1020	-100 to +3	0.001	0.015	± 0.11
Anritsu ML9411A/A1	380 to 1150	-70 to +10	0.01	0.15	± 0.21
Anritsu MA9412A	380 to 1150	-90 to 0	0.01	0.15	± 0.21
Anritsu MA9413A	450 to 1050	-80 to +10	0.01	0.15	± 0.21
Anritsu MU931311A	800 to 1600	-110 to +10	0.001	0.01 to 0.05	± 0.15
Anritsu MU931421A	750 to 1700	-80 to +10	0.001	0.01 to 0.05	± 0.15
EXFO PM-1613	800 to 1700	-85 to +9	0.001	0.015	± 0.21
EXFO LTS-3902	780 to 1625	-73 to +10	0.01	NA	± 0.21
EXFO LTS-3902X	780 to 1625	-60 to +20	0.01	NA	± 0.21
Newport 2832-C-818-SL/CM	400 to 1100	-90 to +33	0.01	0.022	± 0.086
Rifocs 575L	780 to 1550	-80 to +3	0.01	0.05	± 0.25
Rifocs 577L	635 to 850	-75 to +3	0.01	0.05	± 0.25
Tektronix Q82214	400 to 1100	-80 to +17	0.001/0.0001	0.02	± 0.21

[1] represents display resolution and not resolution of the A/D converter
[2] values expressed in % have been converted to dB
[3] or uncertainty
NA – not available

Table 6.8 Parameters of various commercially available fiber-optic switches

Manufacturer	Model	Number of Input × Output Channels	Maximum Insertion Loss (dB)	Maximum Repeatability (dB)	Typical Switching Life (cycles)	Switching Time (ms)
Agilent	86062C	1 × 100	0.8	± 0.025	10^7	330
DiCon	SP-12	1 × 2	1.0	± 0.01	10^7	15
DiCon	VX-5-50	1 × 50	1.2	± 0.02	10^7	1100
EXFO	IQ-91XX	1 × 32	1.2	± 0.01	10^7	1625
JDS Uniphase	SK	1 × 26	0.7	± 0.01	--	465
JDS Uniphase	SP	1 × 100	1.2	± 0.08	--	1575
JDS Uniphase	SV	1 × 32	0.5	± 0.025	--	409
Newport	SPSN-62-12	1 × 2	1.0	± 0.005	10^7	15

Table 6.9 Parameters of various commercially LED light sources

Manufacturer	Model	Center Wavelength (nm)	Wavelength Uncertainty (nm)	Spectral Width (nm)	Output Power (dBm)	Stability (dB)
EXFO	FLS-2101D	850	± 25	< 50	-14	± 0.003
OZ Optics	FOSS-02	810	--	--	--	± 0.025
SIECOR	OS-300	850	± 20	50	-18	± 0.1
Tektronix	TOP130	850	--	55	-13	± 0.05

Table 6.8 lists several commercially available fiber-optic switches and their relevant parameters. For consistency, only equipment with operating wavelengths that include 810 nm, switch sizes of 1 × N were selected (N is maximum value for that model), and that accommodate multimode optical fiber were selected. Insertion loss and its variability (repeatability) are listed, along with the anticipated lifetimes (in switching cycles) and switching times required.

A review of the data shown in Table 6.8 reveals the typical fiber-optic switch insertion-loss repeatability ranges from about ± 0.005 dB to ± 0.025 dB.

Table 6.9 lists a few commercially available LED light sources compatible with multimode fiber optics and operating wavelengths in the 800- to 900-nm range.

Instrument accuracy is found by combining the various uncertainties as before using (5.3). Note that since the variability in the switch's insertion loss equally affects both P_{RX} and P_{MON}, this factor does not directly contribute to ΔP_{INS}. By assuming the spectral characteristics of the source are measured during system calibration, the uncertainty due to wavelength uncertainty can be reduced to a level so insignificant that it can be ignored. Also by assuming simultaneous power measurements (receive and monitor), the effects of transmit power instability are eliminated.

The instrument accuracy will depend exclusively on the power meter used. For power meters with an accuracy of ± 0.09 dB, the instrument accuracy will be ± 0.13 dB. For power meters with an accuracy of ± 0.25 dB, the instrument accuracy will be ± 0.35 dB.

6.2.2 Calibration accuracy

As stated previously, the connector types used in the previous example are again used in this example. Therefore the calibration accuracy analysis presented previously remains valid. Only the cases involving adapter cables are considered in this example.

6.2.3 Overall insertion-loss measurement accuracy

The results of using (5.4) to determine the overall insertion-loss measurement accuracy (ΔIL) are shown in Table 6.10.

For systems configured using the more accurate power meters (± 0.09 dB accuracy), the overall insertion-loss measurement accuracy is about ± 0.33 dB with calibration uncertainty accounting for more than 70 % of this value. However, for systems configured using the less accurate power meters (± 0.25 dB accuracy), the insertion-loss measurement accuracy is almost ± 0.6 dB with more than 70 % of the overall accuracy limited by the power measurement system.

Table 6.10 Insertion-loss measurement uncertainties using commercially available power meters

Insertion-loss measurement uncertainty in system with …	Symbol	Units	Value ($\Delta P_{INS} = \pm 0.13$ dB)	Value ($\Delta P_{INS} = \pm 0.35$ dB)
adapter cables (type 1 & 2 connectors)	ΔIL	dB	± 0.33	± 0.57
adapter cables (type 1 connectors only)	ΔIL	dB	± 0.35	± 0.59

7 Discussion

In cases where uncertainties in power measurement are the dominant factor determining the overall insertion-loss measurement accuracy, techniques to reduce this source of error may be valuable. Therefore, techniques for reducing or managing the specific factors contributing the power measurement uncertainty are addressed individually the following sections.

7.1 Instrumentation accuracy

Based on the preceding analysis the accuracy of the custom-built electronic subsystem (i.e., that part of the measurement system excluding the fiber-optic connectors) is about ± 0.092 dB. If the connector loss could be reduced to an insignificant level (for example novel connectors that employ techniques involving active fiber core alignment have been reported), the accuracy would then be limited to that of the electronic subsystem. This means that the true insertion loss differs from the measured value by less than ± 0.092 dB ($\pm 3\sigma$) 99.74 % of the time, or less than ± 0.061 dB ($\pm 2\sigma$) 95.44 % of the time, or less than ± 0.031 dB ($\pm 1\sigma$) 68.26 % of the time.

The factors dominating this accuracy include the wavelength uncertainty, amplifier gain variations, measurement system nonlinearities, and the finite A/D resolution. Techniques for reducing these factors are addressed separately below.

7.2 Accommodating wavelength variations

For a realizable measurement system, the wavelength of the LED is essentially constant, i.e., LED wavelength is determined by the material properties which are set at the time of manufacture so aging and temperature have only a small impact on this parameter. A scenario where wavelength variations may be a factor in an insertion-loss measurement is shown in Fig. 7.1 below. Here the insertion loss of a multiport fiber-optic device (such as a star coupler) is measured using an array of M light sources (LEDs) and each with their associated power monitors. The light from each LED is characterized by its wavelength (λ_i, i = 1, 2, …, M). The insertion loss through each of the M input ports is measured by sequentially activating a single LED, measuring the monitor power and the receiver power, then extinguishing this LED and activating the next LED. If the LED wavelength uncertainty is $\pm \Delta\lambda$, then the power measurement uncertainty (accuracy) due to wavelength variation (ΔP_λ) is as described in (5.7). To eliminate this uncertainty source, the wavelength of each LED must be measured and recorded during calibration. Therefore, the power measured in the receiver can be adjusted to reflect the change in wavelength. If this process is followed, then ΔP_λ will be essentially driven to zero.

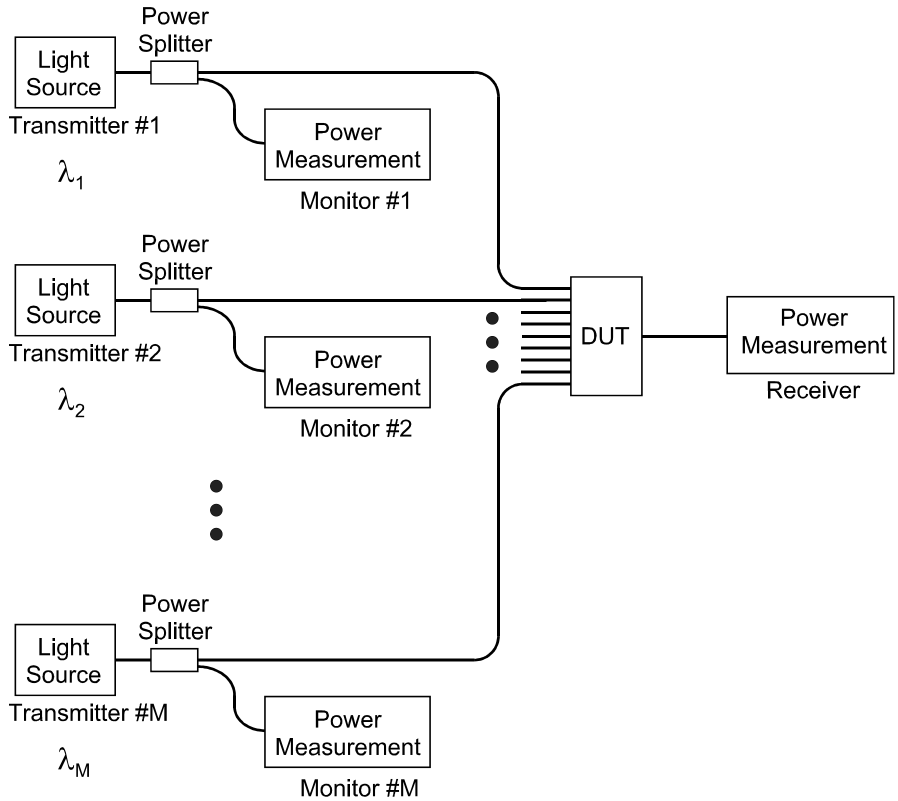

Figure 7.1 Insertion-loss testing on a multiport device using multiple light sources.

7.3 Accommodating amplifier gain variations

Variations in amplifier gain can also play a significant role in determining the instrument accuracy. While the nominal amplifier gain may be specified by the manufacturer or designer, the true gain is factored into the measurements that determine the calibration factor (K_{CAL}). Therefore it is the variation of the gain from its value at calibration that contributes to the power measurement uncertainty due to gain variations (ΔP_{GAIN}). Techniques for monitoring amplifier gain, or maintaining a constant gain, may be available to minimize the effects of this factor.

7.4 Accommodating receiver nonlinearities

While receiver nonlinearities play a secondary role in determining the overall instrument uncertainty, once these other factors are addressed, nonlinearities may become a major factor. Therefore, techniques for minimizing this effect may be useful.

One technique for reducing the effect of receiver nonlinearity is to calibrate the receiver at several different optical power levels, rather than just one level. Therefore several different calibration factors will be produced. A second-order correction could then be applied to the measured power by interpolating the calibration factors to obtain a value appropriate to the estimated power. Implementing this approach significantly reduce the effect of receiver nonlinearities.

7.5 Accommodating limited A/D resolution

Uncertainty due to the limited resolution of the A/D converter can also be addressed, should this factor be a major factor affecting the overall instrument accuracy. Since the uncertainty due to this effect increases as the signal to be digitized is reduced, boosting the signal level (via an electonic amplifier) can ensure that the signal level is large enough (in terms of the dynamic range of the A/D converter) so that this uncertainty factor is reduced to an acceptable level.

An alternative approach would be to use an A/D converter with more resolution (more bits).

8 Conclusions

This document attempts to provide an answer to the question: To what accuracy can insertion-loss measurements be made on low-loss, multi-mode fiber-optic cables, patch cords, and modules having a variety terminations? To answer this question, and to provide insight regarding the factors that dominate the measurement accuracy, a thorough analysis of the measurement process is required. To minimize confusion, relevant terminology is defined for purposes of this analysis. In addition, to limit the discussion to those factors affecting the question at hand, a list of underlying assumptions is provided.

An analysis of a custom-built power measurement system showed an instrument measurement accuracy of about ± 0.092 dB. Using connectors with a maximum specified insertion loss of ± 0.25 to ± 0.30 dB, the calibration accuracy ranged from ± 0.15 dB to ± 0.30 dB, depending on the measurement system configuration and the calibration procedure. Combining the instrument accuracy with the calibration accuracy yields an overall insertion-loss measurement accuracy that ranges from ± 0.18 to ± 0.32 dB. While other factors (such as wavelength variability, amplifier gain variability, receiver nonlinearity, and finite A/D converter resolution) contribute to overall measurement accuracy, calibration uncertainty due to connector loss variability dominates the overall measurement accuracy and can be two to three times larger than these factors.

An analysis of an alternate measurement system composed of commercial optical power measurement equipment, fiber-optic switches, and LED sources showed instrument measurement accuracies ranging from about ± 0.13 dB to ± 0.35 dB. When fiber-optic connector insertion-loss variability was included, the overall insertion-loss measurement accuracy ranged from ± 0.33 dB to ± 0.59 dB. For systems using the more accurate (± 0.10 dB) power measurement equipment, the overall accuracy was dominated by the connector loss variability. However for systems using the less accurate power measurement equipment (± 0.25 dB accuracy) the overall insertion-loss measurement accuracy was dominated by the power measurement system accuracy.

In general, any attempts to improve the overall insertion-loss measurement accuracy to ± 0.1 dB or lower must address the variable connector insertion loss, as the uncertainty introduced by this is the dominant factor in systems with reasonable power measurement accuracies.

9 References

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