Optical Fiber Power Meter Nonlinearity Calibrations at NIST

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We describe a system for measuring the response nonlinearity of optical fiber power meters and detectors over a wide power dynamic range at telecommunication wavelengths. The system uses optical fiber components and is designed to accommodate commonly used optical fiber power meters. The system also measures the range discontinuities between neighboring power ranges or scale settings of the optical fiber power meter. Measurements with this system yield correction factors for all power ranges of the meter. The measurement system is capable of producing results which have standard deviations as low as 0.01 %. The measurement uncertainties associated with the system are described.

Key words: calibration; detector; linearity; measurement service; nonlinearity; optical fiber power meter; optical power; range discontinuity; uncertainty.

1. Introduction

There are several methods currently used for the measurement of optical fiber power meter (OFPM) or detector nonlinearity: differential, attenuation, and superposition. These methods were compared analytically using a unified mathematical expression for nonlinearity [1-3]. Based on these results, we developed a system, which uses a superposition method known as the triplet method. This method relies on the principle that for a linear OFPM, the sum of the OFPM outputs corresponding to inputs from two individual beams should equal the output when the two beams are combined and incident on the OFPM at the same time. The triplet method does not require a standard; a measurement system based on the triplet method is the standard by itself.

2. Measurement of Nonlinearity and Range Discontinuity

Generally, an OFPM has a dynamic range of more than 60 dB with many meters exceeding 90 dB. To achieve these dynamic ranges, an OFPM is designed to switch ranges during optical power measurements. The power ranges have their own gains or amplifications, which often differ by a factor of 10. When the meter switches from one range to another, it is critical that two neighboring ranges indicate the same power. If the power readings at these two ranges are not the same, then the OFPM has a range discontinuity (assuming the power has remained constant). A simplified schematic of a typical OFPM is depicted in Figure 1.

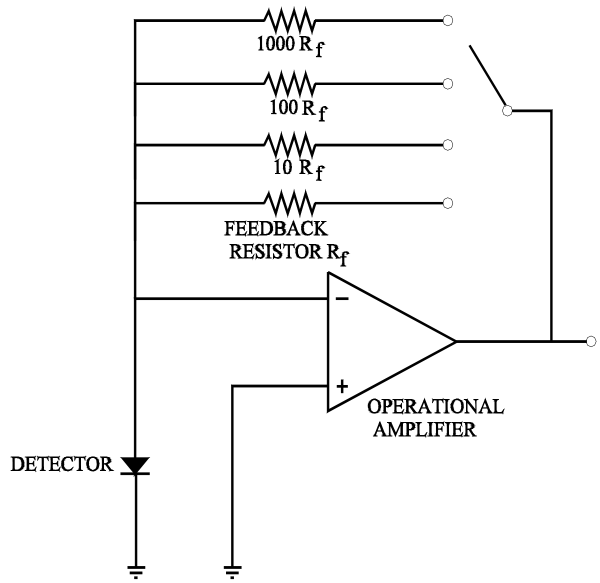

Figure 1. Simplified schematic of a typical optical power meter.

The NIST nonlinearity system is capable of measuring the nonlinearity of OFPMs over a dynamic range of more than 60 dB at the three nominal telecommunication wavelengths: 850, 1300, and 1550 nm. This system uses optical fiber components and is designed to accommodate commonly used OFPMs and other optical detectors. The system also measures the range discontinuity between neighboring power ranges or scale settings of the OFPM. Measurements with this system yield a correction factor for each power range of an OFPM. Note: for a bare detector, the ranges may be the electrical voltage or current ranges of the output electronics.

2.1 Definition and Basic Expressions

The nonlinearity of an OFPM is defined as the relative difference between the responsivity at an arbitrary power and the responsivity at the calibration power (i.e., the power at which the meter was calibrated). This definition can be expressed as

$$\Delta_{NL}(P;P_c) = \frac{R(P) - R(P_c)}{R(P_c)}, \tag{1}$$

where R(P) = V/P is the responsivity of the OFPM at incident optical power P; the subscript c indicates the calibration point, and V is the OFPM output, which can be electrical current, voltage, or the display reading from the OFPM. A function that describes the relationship between the incident optical power P and an OFPM or detector output is called the response function and is expressed as:

$$V = V(P). \tag{2}$$

The response function is depicted in Figure 2. We can express the nonlinearity of eq (1) in terms of the response function:

$$\Delta_{NL}(P;P_c) = \frac{V(P)P_c}{V(P_c)P} - 1. \tag{3}$$

The inverse function (when the dependent and independent axes are switched) of the response function is called the conversion function and is depicted in Figure 3. This conversion function converts the output V to the input power P and is expressed as

$$P = P(V). \tag{4}$$

The response function and the conversion function represent the same physical quantity in inverted variables. Consequently, the nonlinearity can equivalently be expressed and calculated in terms of the response function and input power P.

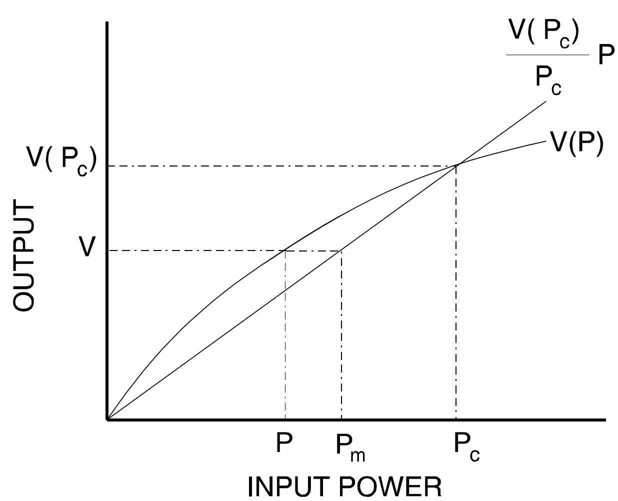

Figure 2. A response function.

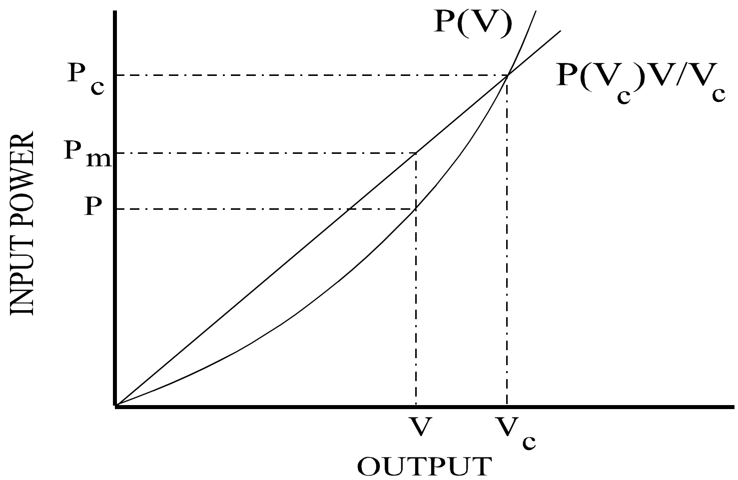

Figure 3. A conversion function.

In practice, it is often more convenient to use the conversion function rather than the response function. We can define the nonlinearity in terms of the output V as

$$\Delta_{NL}(V;V_c) = \frac{P(V_c)V}{P(V)V_c} - 1. \tag{5}$$

2.2 Polynomial Expression for Conversion Function

When the nonlinearity is small, a polynomial can represent the conversion function well [4,5]; that is

$$P(V) = \sum_{k=1}^{n} a_k V^k, \tag{6}$$

where n is the order of the polynomial and a_k are the coefficients of the polynomial. The coefficients a_k correspond to a calibrated conversion function [1].

The output responses of the commonly used photodiodes, Si, Ge, or InGaAs, are exponential (see conversion function in Figure 3) with respect to the input power. However, they are often used in nearly short-circuited or reverse-biased configurations to achieve a linear response. As a result, their responses can be approximated as polynomials produced by the Taylor-series expansion of the form shown in eq (6), where the zero-order term is not included because we always measure the dark signal and later subtract it from the output of an OFPM. With the assumption of

$$\sum_{k=2}^{n} \frac{a_k}{a_1} V^{k-1} \ll 1,$$

the nonlinearity Δ_{NL} of eq (5) can be approximated by (for the nonlinearity of less than 1 %, the approximation error is less than 0.01 %)

$$\Delta_{NL}(V;V_c) \approx -\sum_{k=2}^{n} \frac{a_k}{a_1}(V^{k-1} - V_c^{k-1}). \qquad (7)$$

If we divide all the coefficients a_k in eq (6) by the first coefficient a_1, the polynomial thus obtained is called the normalized conversion function, denoted by p(V) and expressed as

$$p(V) = V + \sum_{k=2}^{n} b_k V^{k}, \qquad (8)$$

where $b_k = a_k/a_1$. The coefficients b_k correspond to an uncalibrated conversion function described in reference [1]. Typically, n is equal to 3.

The nonlinearity can be expressed as

$$\Delta_{NL}(V;V_c) \approx -\sum_{k=2}^{n} b_k(V^{k-1} - V_c^{k-1}). \qquad (9)$$

2.2.1 Triplet Superposition Method

In the triplet superposition method, a group of three power measurements is made, two for individual powers from each beam and one for the combination of the two. For the i^{th} group of measurements, we have a set of three equations:

$$\begin{cases} p_{1i} = V_{1i} + \sum_{k=2}^{n} b_k V_{1i}^{k}, \\ p_{2i} = V_{2i} + \sum_{k=2}^{n} b_k V_{2i}^{k}, \\ p_{1i} + p_{2i} = V_{3i} + \sum_{k=2}^{n} b_k V_{3i}^{k}, \end{cases} \tag{10}$$

where the p_i are arbitrary unknowns and the V_i are measured output values. A new equation is formed by subtracting the first and second equations from the third equation while eliminating the unknown p_i in the group of the three equations in eq (10):

$$(V_{3i} - V_{1i} - V_{2i}) + \sum_{k=2}^{n} b_k (V_{3i}^{k} - V_{1i}^{k} - V_{2i}^{k}) = 0. \tag{11}$$

The coefficients b_k can be obtained by linear least-squares fitting of the measured data. The three measurement runs are usually made in immediate succession, which helps reduce the uncertainty that might occur due to drift of the laser source output. The details of the measurements are described in Section 3.

2.3 Correction Factor for Nonlinearity and Range Discontinuity

While calibration gives the true relationship between the input power and the OFPM reading (output) at the calibration point, the measurement of nonlinearity and range discontinuity, together with calibration, provides this input-output relation at any power over the whole dynamic range of the OFPM. It is, therefore, convenient to express the measured nonlinearity, $\Delta_{NL}(V;V_c)$ in terms of the conversion function $P = P(V)$, which relates the input power P to the output V, referred to the calibration output V_c.

We denote the range setting of the OFPM with brackets; [m] denotes some range m (m = 1, 2, 3,...), and [c] is the range where the reference power is used. Calibration determines a_1 in range [c] where the calibration reference point is selected; P_c is the calibration power at a reference power of approximately 100 μW and V_c is the calibration output as shown below:

$$a_1[c] = \frac{P_c}{V_c + \sum_{k=2}^{n} b_k[c] V_c^k} . \tag{12}$$

The true input power P is obtained from the OFPM reading V for any given range m by

$$P = \frac{V}{F_c \cdot CF[m]}, \tag{13}$$

where $F_c = V_c/P_c$ is the calibration factor described in reference [6] and CF[m] is a correction factor for nonlinearity over the entire range m and range discontinuity in any range (except the range that corresponds to the lowest power used in a nonlinearity calibration). This correction factor can be calculated by:

$$CF[m] = \frac{a_1[c]}{a_1[m]} \times \frac{1 + \sum_{k=2}^{n} b_k[c] V_c^{k-1}}{1 + \sum_{k=2}^{n} b_k[m] V^{k-1}} , \tag{14}$$

where the discontinuity coefficients $a_1[m]$ outside range [c] are determined using eqs (15) and (16):

$$\frac{a_1[c]}{a_1[m]} = \frac{a_1[c]}{a_1[c+1]} \times \cdots \times \frac{a_1[m-1]}{a_1[m]} \qquad \text{for } m > c, \tag{15}$$

or

$$\frac{a_1[c]}{a_1[m]} = \frac{1}{\frac{a_1[m]}{a_1[m+1]} \times \cdots \times \frac{a_1[c-1]}{a_1[c]}} \qquad \text{for } c > m. \tag{16}$$

The coefficients of the noncalibrated conversion function $b_k[m]$ in eq (14), are determined from the measured nonlinearity by means of a least squares curve fitting. The ratio of a_1 between two neighboring ranges $a_1[m]/a_1[m + 1]$ is determined by the measured range discontinuity. Typically, we use a third-order polynomial (n = 3) to calculate the correction factor in eq (14). Each range of an OFPM has its own correction factor.

3. Nonlinearity Measurement System

The NIST OFPM nonlinearity system is depicted in Figure 4. The system is fully automated. After the measurements are completed (typically in 3 h), the computer program analyzes the data and prints the calibration data in a table form. We use high-power, single-mode, fiber-pigtailed lasers whose powers are stabilized. All the lasers are temperature controlled for power and wavelength stability. An external optical attenuator with a dynamic range of more than 60 dB provides variable optical power. The output of the attenuator is divided into two approximately equal parts by using a fiber splitter; one of the splitter arms has an additional length of fiber (approximately 100 m, compared to the coherence length of the laser of only a few centimeters) to avoid interference. A computer-controlled shutter is inserted into a collimated beam in each arm. Both signals are combined in a fiber coupler which has an FC/APC connector at the output to decrease reflections back to the laser and other components of the measurement system. We use single-mode fiber components (e.g., splitters and couplers) throughout the system. Loose system fibers are wrapped on spools 5 cm in diameter to minimize transient microbend losses. Also, in this regard, all fibers are securely fixed so that they cannot move during the measurements. All the lasers are of Fabry-Perot type and have several longitudinal (spectral) modes (see Appendix A).

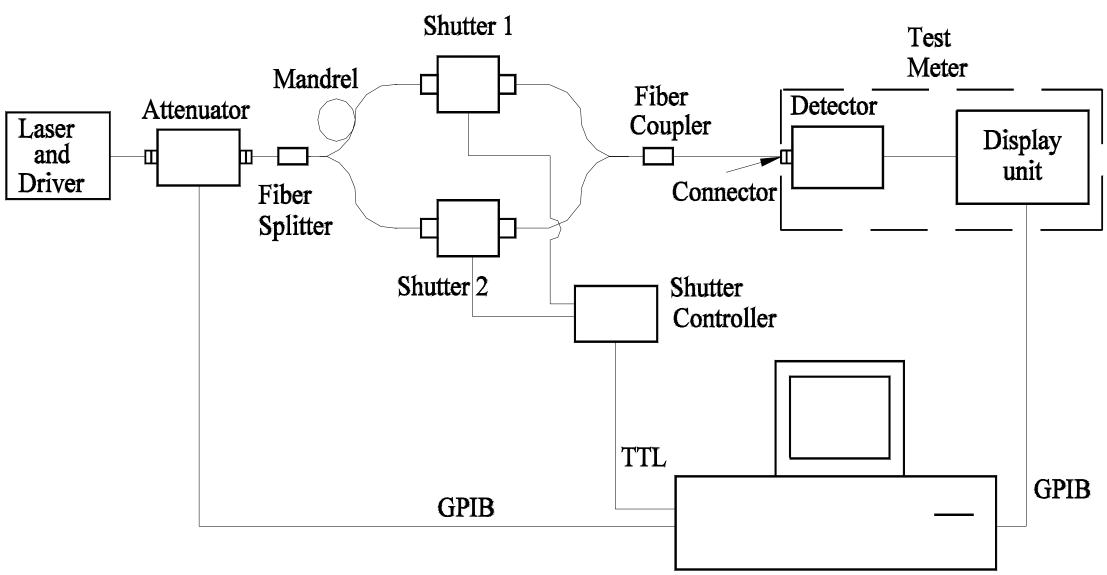

Figure 4. The nonlinearity measurement system.

The data are acquired using the triplet superposition method. The measurements are performed by taking three power readings from the OFPM: (1) when the shutter 1 is open (1 s) and shutter 2 is closed, (2) when both shutters are open (1 s), and (3) when the shutter 1 is closed and shutter 2 is open (1 s). These three power measurements are called a triplet. Shutters are controlled by the computer, which sends a TTL signal to the shutter controller. This sequence is then repeated at different powers. The OFPM response is linear when the sum of the two individual power readings is equal to the combined-power reading. We usually divide each power range of an OFPM into 10 parts or sets spaced equally in the logarithmic scale. Each set is a triplet measurement taken three times and averaged. Each single measurement in a triplet is taken three times as well, and the result is averaged. Thus, there are 27 single measurements for each set. Generally, there are total of 270 single measurements per single power range. If an OFPM has six ranges, the computer will take 1,620 single measurements for one run. The computer takes three runs to calculate the final results. Thus, to measure an OFPM nonlinearity, the computer will collect nearly 5,000 single measurements. For each measurement run, the averaged data, grouped in three columns are saved on the hard drive of the computer. Each row of the data represents a measurement set of a triplet.

To measure the range discontinuity (offsets between ranges or scales), readings are taken at the lower-power end of each range and compared to the readings on the higher-power end of the next lower range at the same input power. Generally, three sets of measurements for each range are taken to calculate the range discontinuity. When shutter 1 is closed and shutter 2 is open, five single measurements are taken (and averaged) for two neighboring ranges. Then, three values of the range discontinuity (for each range except the lowest one) is stored in the data file. The background or offset of each range is measured and the value is subtracted from the signal.

Using the system shown in Figure 4, the nonlinearity of an OFPM is characterized over the power between 1.5 nW and 3.5 mW at a wavelength of 1314 nm. Sample results obtained on a NIST OFPM are presented in Table 1 and shown graphically in Figure 5, in which a symbol represents a power range of an OFPM. The correction factors result from meter nonlinearity within each range, combined with the range discontinuity. Most OFPMs use power ranges in decibels/meter units. **Note:** decibel/meter is not an SI unit, but is related to a power of 1 mW as 10 log (x), where x is an unknown power in milliwatts. Each correction value listed in the Table 1 is the average of six correction factors (except the 10 dBm or 10 mW range, which is represented by only three points due to a limited laser power) found throughout that range. If the nonlinearity of an OFPM is not negligible, it is necessary to provide correction factors at each power, as for the highest power range in Figure 5, and avoid averaging correction factors as it is done for ranges with small nonlinearities. The flow chart of the measurement is shown in Appendix B.

To correct for nonlinearity and range discontinuity, the OFPM readings should by **divided** by the appropriate correction factors. The standard deviation of the correction factors for each range in Table 1 was calculated using three data runs. A sample copy of a calibration report is provided in Appendix C.

Table 1. Nonlinearity and range discontinuity correction factors.

Meter range [m] (dBm)*		Output power	Mean correction factor	Standard deviation (%)
1:	10	1.5-3.5 mW	1.007	0.30
2:	0	0.15-2 mW	0.9995	0.06
3:	-10 [c]	15-200 μW	1.000	0.01
4:	-20	1.5-20 μW	0.9993	0.02
5:	-30	0.15-2 μW	1.003	0.04
6:	-40	15-200 nW	1.002	0.06
7:	-50	1.5-20 nW	1.003	0.06

***** dBm is not an SI unit, but is related to a power of 1 mW as 10 log (x), where x is an unknown power in milliwatts.

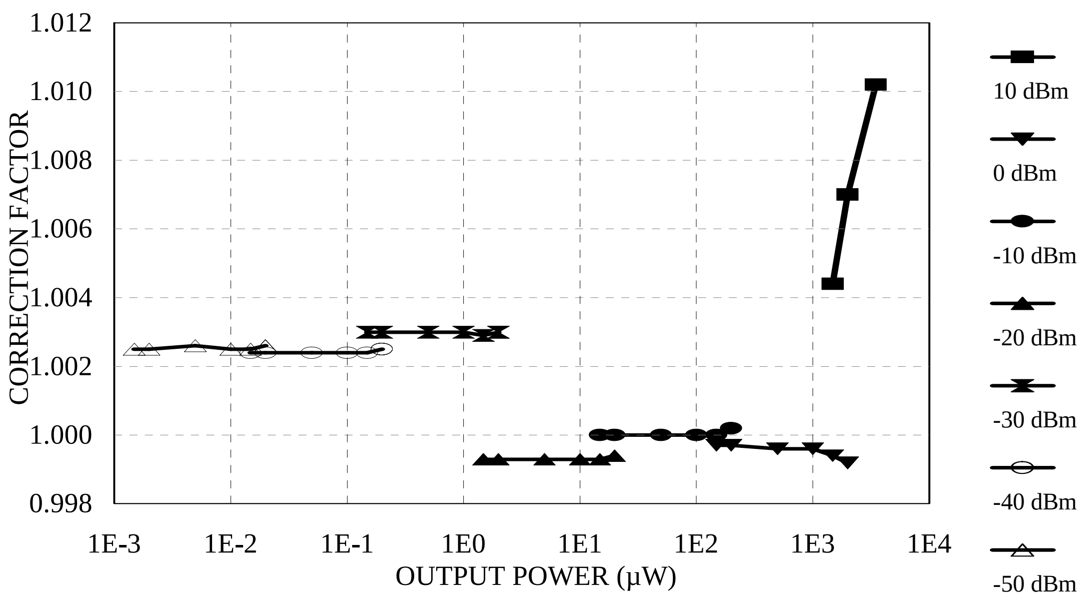

Figure 5. Correction factor versus output power.

4. Uncertainty Assessment

In this section we assess the associated uncertainty of the OFPM nonlinearity measurements. The uncertainty estimates for the NIST OFPM nonlinearity measurements are described and combined using the referenced guidelines [7]. To establish the uncertainty limits, the uncertainty sources are separated into Type A, whose magnitudes are obtained statistically from a series of measurements, and Type B, whose magnitudes are determined by subjective judgement.

The Type A uncertainty components are assumed to be independent and, consequently, the standard deviation, S_r, for each component is

$$S_r = \sqrt{\frac{\sum_i x_i^2 - \frac{(\sum_i x_i)^2}{N}}{N-1}} \quad , \tag{17}$$

where the x_i values represent the individual measurements and N is the number of x_i values used for a particular Type A component. The standard deviation of the mean is $S_r/N^{½}$, and the total standard deviation of the mean is $[\sum(S_r^2/N)]^{½}$, where the summation is carried out for all Type A components.

All the Type B components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\delta_s$, and zero probability of being outside that region). If the distribution is rectangular, the standard deviation, σ_s, for each Type B component is equal to $\delta_s/3^{½}$ and the total ‘standard deviation’ is $(\sum\sigma_s^2)^{½}$, where the summation is performed over all Type B components.

The combined uncertainty is determined by combining the Type A and Type B standard deviations in quadrature; the expanded uncertainty is obtained by multiplying this result by a coverage factor of **2**. The expanded uncertainty, U, is then

$$U = 2\sqrt{\sum_s \sigma_s^2 + \sum_r \frac{S_r^2}{N}} \quad . \tag{18}$$

The number of decimal places used in reporting the mean values of the calibration factor are determined by expressing the expanded NIST uncertainty in percentage to two significant digits. In Table 2, we describe the nonlinearity of an OFPM calibration uncertainty using Type A and Type B components as follows:

Type A
Repeatability: This is an uncertainty due to the scatter of data points around the measurement average obtained from three calibration runs on the OFPM being calibrated.

Type B
a. Laser power stability: During the nonlinearity calibration of an OFPM, changes in optical power such as drift or fluctuations can cause a possible error. The power stability is measured during the time interval in which the three measurements are taken. The low power (when an individual shutter is open) is measured before and after the high power (when both shutters are open). The value for laser stability is found by measuring the drift for each laser source. The slope of the drift (percent per second) is then multiplied by the interval that the three shutters are open (3 s) during an actual nonlinearity calibration. The maximum measured value of the power drift is 0.21 % at 850 nm, and 0.09 % at 1300 nm and 1550 nm. The standard uncertainty for laser stability is $0.21/(2\sqrt{3}) = 0.06$ % at 850 nm, and $0.09/(2\sqrt{3}) = 0.03$ % at 1300 and 1550 nm.

b. Polynomial truncation: The conversion function of an OFPM is a least-squares fit to a third-order polynomial. The uncertainty is due to truncation of the polynomial of higher orders. The maximum value of the error can be found from Figure 9 of reference [1] and is equal to 0.007 %. The standard uncertainty is $0.007/(2\sqrt{3}) = 0.002$ %.

c. Test meter spectral responsivity: This uncertainty is caused by drift of the source wavelength and a drift of the optical spectrum analyzer during each triplet measurement. The size of the uncertainty depends on the absorbing material of the power meter detector. The value is estimated based on the spectral responsivity curves for Si, Ge, and InGaAs detectors. We assume a combined variation for the lasers wavelengths and accuracy of the optical spectrum analyzer of 0.1 nm.

Table 2 lists typical spectral responsivity slopes (percent per nanometer) for Si, Ge, and InGaAs detectors used in most OFPMs.

Table 2. Spectral responsivity slope (percent per nanometer) for Si, Ge, and InGaAs detectors.

Diode type	Wavelength (nm)		
	850	1300	1550
Si	0.14	NA	NA
Ge	0.48	0.14	0.92
InGaAs	0.53	0.09	0.05

Table 3. Standard uncertainty (%) for spectral responsivity for Si, Ge, and InGaAs detectors.

Diode Type	Wavelength (nm)		
	850	1300	1550
Si	0.004	NA	NA
Ge	0.014	0.004	0.027
InGaAs	0.015	0.003	0.001

Table 3 presents the standard uncertainty values for Si, Ge, and InGaAs detectors. The standard uncertainty due to this wavelength effect is equal to the appropriate value from Table 2 multiplied by 0.1 nm and divided by $2\sqrt{3}$.

d. Equation approximation: This uncertainty is due to the approximation defined by eq (7). The uncertainty is of second-order in magnitude, i.e., if the nonlinearity is 1 %, then the uncertainty is $(0.01)^2$ or 10^{-4}. This uncertainty depends on the value for the nonlinearity in each case. The maximum uncertainty will be divided by $(2\sqrt{3})$.

e. Polarization: This uncertainty is due to effects caused by changes in polarization of the incident power during each triplet measurement set. This uncertainty is related to polarization dependent loss (PDL) of the nonlinearity system. Polarization uncertainty of the nonlinearity system is assumed to be small because we take a large number of measurements (810 measurements per one power range) and because measurement time scales are short compared to changes in the system polarization state. The PDL of the nonlinearity system was measured using a random-polarization generator. The maximum value of the system PDL is 0.002 dB or 0.05 %. The standard uncertainty is $0.05/(2\sqrt{3}) = 0.014$ %.

Tables 4 through 6 list typical measurement uncertainties for calibrations of OFPMs which use Si, Ge, and InGaAs detectors, respectively. The exact values of these various components change for the particular measurement conditions at the time of the measurement.

Table 4. Example of nonlinearity measurement uncertainties for a Si optical fiber power meter at 850 nm.

Source	Standard uncertainty (type) (%)
Laser stability @ 850 nm	0.06 (B)
Polynomial truncation	0.002 (B)
Test meter spectral responsivity @ 850 nm (Si)	0.004 (B)
Equation approximation*	0.026 (B)
Polarization	0.014 (B)
Repeatability (N = 3)	0.05 (A)
Combined uncertainty	0.073
Expanded uncertainty (k = 2)	0.15

* This uncertainty depends on the nonlinearity value for each particular case.

Table 5. Example of nonlinearity measurement uncertainties for a Ge optical fiber power meter at 1300 nm.*

Source	Standard uncertainty (type) (%)
Laser stability @ 1300 nm	0.03 (B)
Polynomial truncation	0.002 (B)
Test meter spectral responsivity @ 1300 nm (Ge)	0.004 (B)
Equation approximation**	0.003 (B)
Polarization	0.014 (B)
Repeatability (N = 3)	0.07 (A)
Combined uncertainty	0.053
Expanded uncertainty (k = 2)	0.11

* For other wavelengths, use the appropriate uncertainty arising from a test meter spectral responsivity (Table 3).

** This uncertainty depends on the nonlinearity value for each particular case.

Table 6. Example of nonlinearity measurement uncertainties for a InGaAs optical fiber power meter at 1550 nm.*

Source	Standard uncertainty (type) (%)
Laser stability @ 1550 nm	0.01 (B)
Polynomial truncation	0.002 (B)
Test meter spectral responsivity @ 1550 nm (InGaAs)	0.0014 (B)
Equation approximation**	0.012 (B)
Polarization	0.014 (B)
Repeatability (N = 3)	0.03 (A)
Combined uncertainty	0.039
Expanded uncertainty (k = 2)	0.08

* For other wavelengths, use the appropriate uncertainty arising from a test meter spectral responsivity (Table 3).

** This uncertainty depends on the nonlinearity value for each particular case.

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5. References

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Appendix A. Laser Diode Optical Spectra

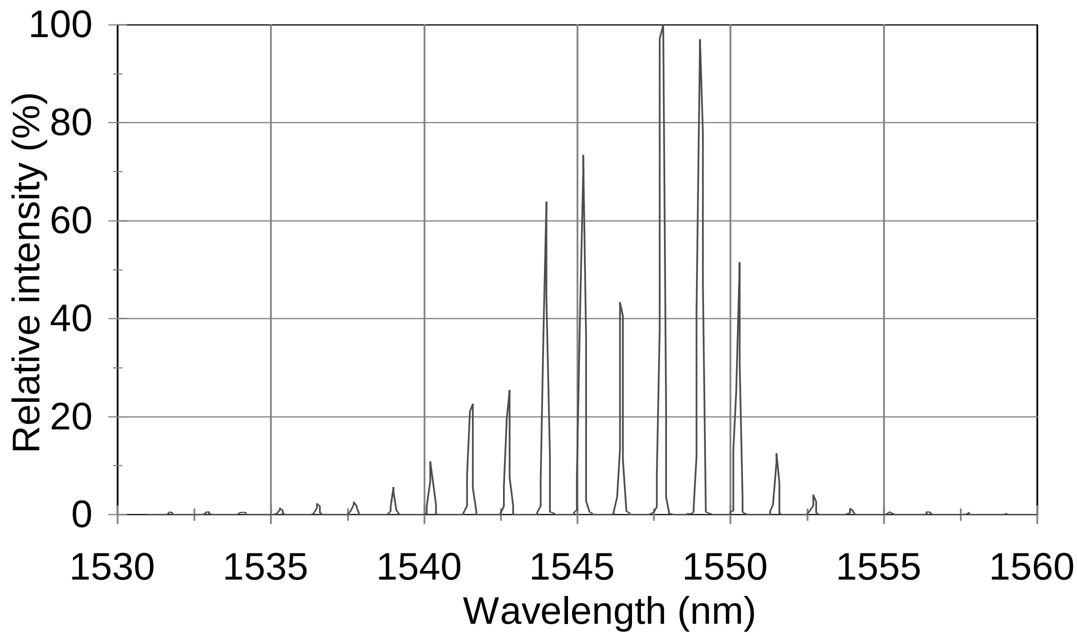
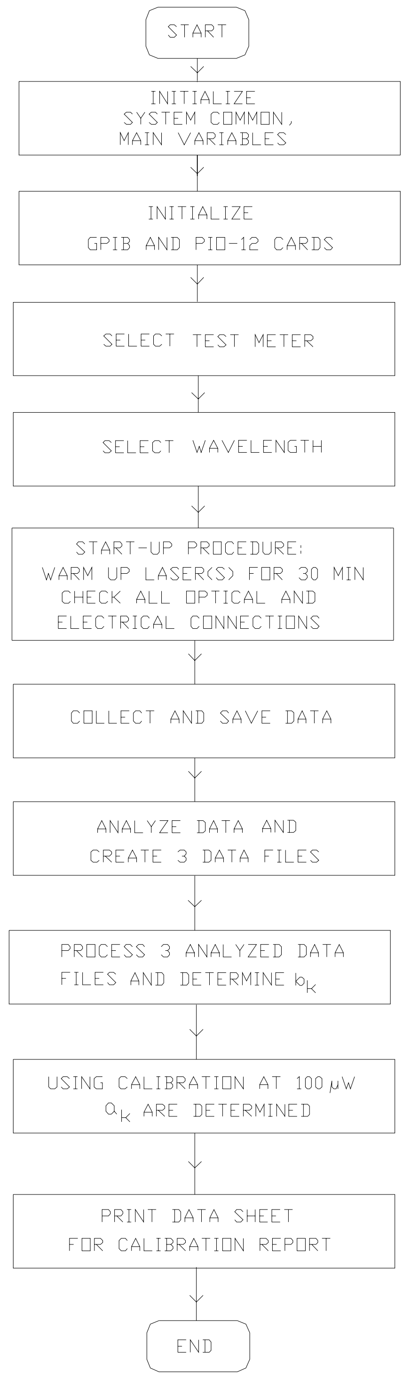


Figure A-1. Optical spectra of a typical laser diode used in the linearity calibration system.

Appendix B. Measurement Flow Chart



U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ELECTRONICS & ELECTRICAL ENGINEERING LABORATORY
Boulder, Colorado 80303

REPORT OF NONLINEARITY CALIBRATION for

OPTICAL POWER METER
Meter's Manufacturer
Model Number
with Sensors
Model Number X, Serial Number 1
Model Number Y, Serial Number 2

Submitted by:

Company name
Address

Nonlinearity Measurement Summary
Using the system shown in Figure 1, the nonlinearity of the optical fiber power meter (OFPM) was characterized over the following ranges: (1) 150 pA to 600 μA at a wavelength of 860 nm for Model X with S/N 1 (Si), and (2) 150 pA to 600 μA at 860 nm, 150 pA to 2.0 mA at 1314 nm and 1542 nm for Model Y with S/N 2. The data were acquired and analyzed using the triplet superposition method in which measurements were performed by taking sets of three power readings from the test meter with: (1) shutter 1 open, shutter 2 closed, (2) both shutters open, and (3) shutter 1 closed, shutter 2 open. This sequence was then repeated at different powers. In principle, the detector is considered linear when the sum of the two individual power readings is equal to the combined power reading. The actual equations used to characterize the degree of nonlinearity and resulting correction factors are discussed in the next section of this report. To measure range discontinuity (i.e., offsets between range or scale settings), readings were taken at the lower power end of each range and compared to the readings on the higher power region of the next lower range (if available) at a constant power.

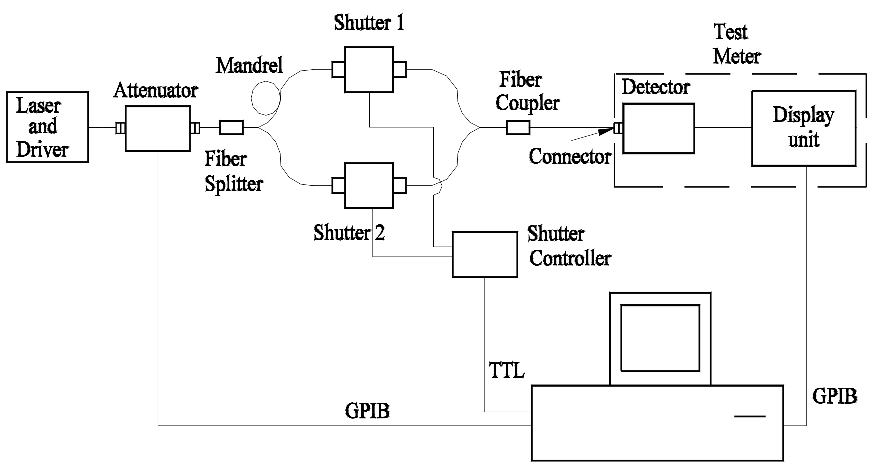


Figure 1. The nonlinearity measurement system.

Folder No. & NISTID: 26000 & 81300
Date of Report: April 30, 2000
Reference: P.O. No. 2121 04/15/00

OPTICAL POWER METER
Meter's Manufacturer
Model Number, Serial Number
with Sensors
Model Number X, Serial Number 1
Model Number Y, Serial Number 2

The results of these measurements are presented in Tables 1 through 4 and shown graphically in Figures 2 through 5. To correct for nonlinearity and range discontinuity, the OFPM readings should by **divided** by the appropriate correction factors in Tables 1 through 4. The correction factors result from meter/detector nonlinearity within each range combined with the range discontinuity (i.e., offsets between ranges). Except for the third, fourth, and fifth ranges for Model Y, S/N 2 detector at 860 nm, each correction value listed in the table is the average of six correction factors found throughout that particular range. Because of the observed nonlinearity, the correction factors for these ranges at 860 nm are for individual powers rather than for the entire range. The uncertainty values listed in Table 1 through 4. The laboratory temperature during these measurements was 22 °C (±2 °C) and the relative humidity was 11 % (±4 %).

Table 1. Nonlinearity correction factors (CF) at 860 nm for optical fiber power meter, Model Number X, Serial Number 1.

Meter/scale range	Output current	CF	Standard deviation for 3 runs (%)	Expanded uncertainty of CF (%)
3	150-600 μA	1.000	0.08	0.12
4	15-200 μA	1.001	0.04	0.08
5	1.5-20 μA	1.000	0.02	0.07
6	150-2000 nA	0.9998	0.03	0.08
7	15-200 nA	0.9993	0.03	0.08
8	1.5-20 nA	0.9995	0.05	0.09
9	150-2000 pA	0.9988	0.03	0.08

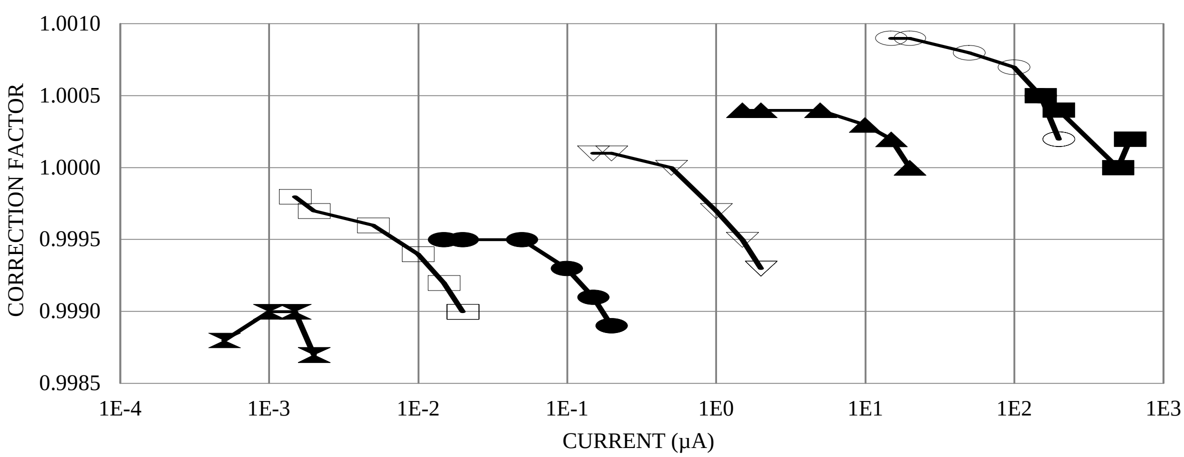


Figure 2. Correction factor versus output current at 860 nm for optical fiber power meter, Model Number X, Serial Number 1.

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Table 2. Nonlinearity correction factors (CF) at 860 nm for optical fiber power meter, Model Number Y, Serial Number 2.

Meter/scale range	Output current	CF	Standard deviation for 3 runs (%)	Expanded uncertainty of CF (%)
	600 µA	1.014	0.02	0.08
3	200 µA	1.006	0.01	0.08
	150 µA	1.004	0.01	0.08
	200 µA	1.005	0.02	0.08
4	100 µA	1.002	0.00	0.07
	20 µA	0.9979	0.01	0.08
	20 µA	0.9969	0.04	0.09
5	10 µA	0.9963	0.03	0.08
	2 µA	0.9954	0.05	0.09
6	150-2000 nA	0.9948	0.03	0.08
7	15-200 nA	0.9941	0.02	0.08
8	1.5-20 nA	0.9941	0.05	0.09
9	150-2000 pA	0.9932	0.08	0.12

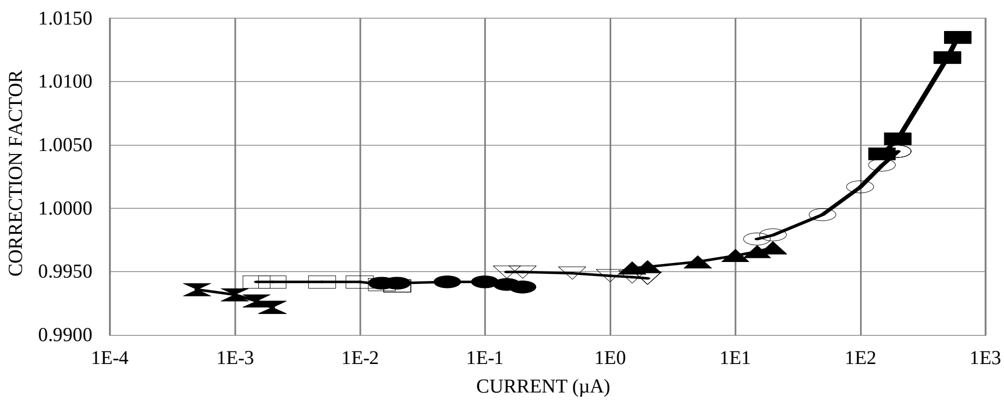

Figure 3. Correction factor versus output current at 860 nm for optical fiber power meter, Model Number Y, Serial Number 2.

Table 3. Nonlinearity correction factors at 1314 nm for optical fiber power meter, Model Number Y, Serial Number 2.

Meter/scale range	Output current	CF	Standard deviation for 3 runs (%)	Expanded uncertainty of CF (%)
3	0.15-2 mA	0.9999	0.05	0.07
4	15-200 μA	1.000	0.03	0.05
5	1.5-20 μA	0.9998	0.03	0.05
6	0.15-2 μA	0.9995	0.04	0.06
7	15-200 nA	0.9992	0.03	0.05
8	1.5-20 nA	0.9993	0.02	0.04
9	150-2000 pA	0.9984	0.08	0.10

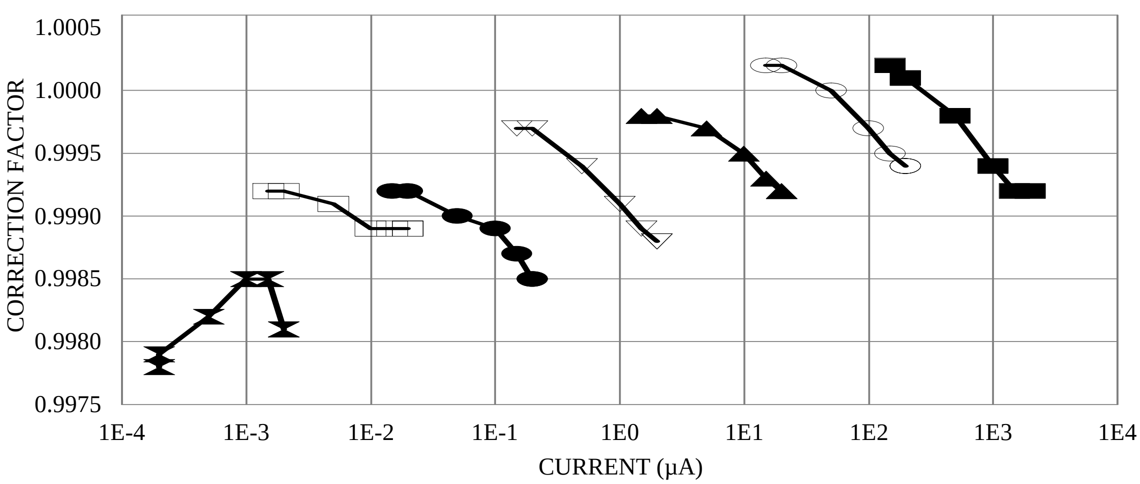

Figure 4. Correction factor versus output current at 1314 nm for optical fiber power meter, Model Number Y, Serial Number 2.

Table 4. Nonlinearity correction factors (CF) at 1542 nm for optical fiber power meter, Model Number Y, Serial Number 2.

Meter/scale range	Output current	CF	Standard deviation for 3 runs (%)	Expanded uncertainty of CF (%)
3	0.15-2 mA	1.001	0.06	0.08
4	15-200 μA	1.000	0.04	0.06
5	1.5-20 μA	0.9997	0.03	0.05
6	0.15-2 μA	0.9991	0.04	0.06
7	15-200 nA	0.9987	0.03	0.05
8	1.5-20 nA	0.9985	0.05	0.07
9	150-2000 pA	0.9990	0.17	0.20

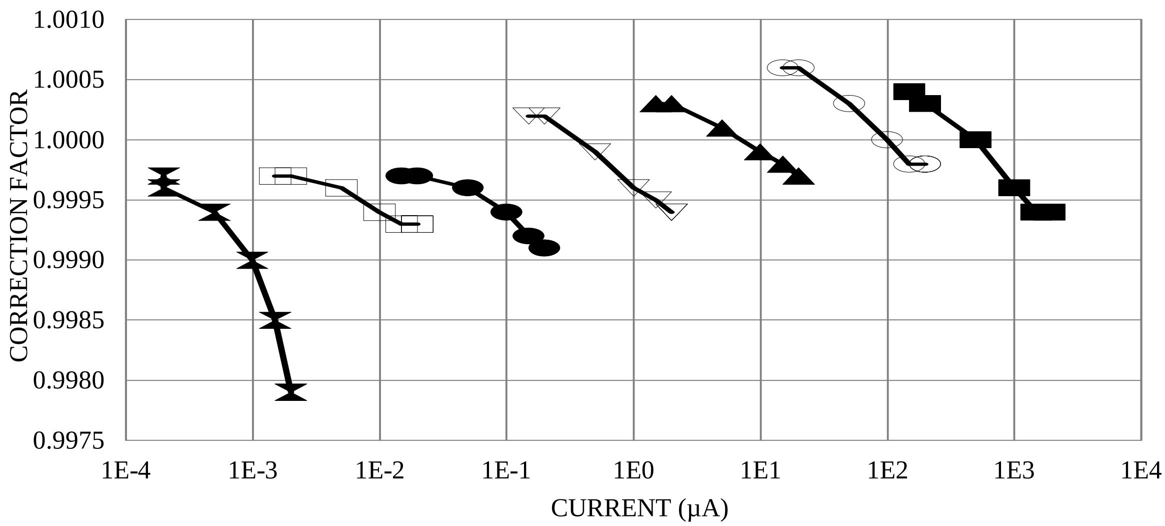

Figure 5. Correction factor versus output current at 1542 nm for optical fiber power meter, Model Number Y, Serial Number 2.

OPTICAL POWER METER
Meter's Manufacturer
Model Number, Serial Number
with Sensors
Model Number X, Serial Number 1
Model Number Y, Serial Number 2

Correction Factor for Nonlinearity and Range Discontinuity

The nonlinearity of the OFPM and associated correction factors were found using the following guidelines. As mentioned earlier in the report, the outputs corresponding to the two individual beams and their combination are measured at different powers in each measurement range of the OFPM. Range discontinuity is also measured at several overlapping powers between two neighboring ranges.

The relationship between the incident power P and its corresponding reading V of the OFPM on any range, m is expressed as:

$$P = a_1[m](V + \sum_{k=2}^{n} b_k[m]V^k), \tag{1}$$

where n is the order of the polynomial, n = 3, and m indicates the measurement range. $b_k[m]$ are determined from the measured nonlinearity by means of the least squares curve fitting. The range discontinuity between two neighboring ranges, m and m + 1, is found from $a_1[m]/a_1[m + 1]$.

When the OFPM is calibrated at power P_c which produces power meter reading, V_c in range [c], the calibration factor F_c is determined by $F_c=V_c/P_c$. The correction factor CF[m] due to both nonlinearity and range discontinuity at any power reading V in any range [m] can be calculated by:

$$CF[m] = \frac{a_1[c]}{a_1[m]} \times \frac{1 + \sum_{k=2}^{n} b_k[c]V_c^{k-1}}{1 + \sum_{k=2}^{n} b_k[m]V^{k-1}}, \tag{2}$$

where

$$\frac{a_1[c]}{a_1[m]} = \frac{a_1[c]}{a_1[c+1]} \times \cdots \times \frac{a_1[m-1]}{a_1[m]} \qquad \text{for } m > c, \tag{3}$$

or

$$\frac{a_1[c]}{a_1[m]} = \frac{1}{\frac{a_1[m]}{a_1[m+1]} \times \cdots \times \frac{a_1[c-1]}{a_1[c]}} \qquad \text{for } c > m. \tag{4}$$

The incident power P[m] is obtained from the power meter reading V by for any given range m by

$$P[m] = \frac{V}{F_c \cdot CF[m]}. \tag{5}$$

Tables 1 through 4 list CF values for each measurement range. These CF values represent an average of the individual CF values found at various power levels within the range (except the ranges from 3 through 5 described in Table 2).

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Uncertainty Assessment
The uncertainty estimates in Tables 1 through 4 for the NIST linearity measurements are described and combined using the guidelines of NIST Technical Note 1297. To establish the uncertainty limits, the uncertainty sources are separated into Type A, whose magnitudes are obtained statistically from a series of measurements, and Type B, whose magnitudes are determined by subjective judgement.

The Type A uncertainty components are assumed to be independent and, consequently, the standard deviation, S_r, for each component is

$$S_r = \sqrt{\frac{\sum_i x_i^2 - \frac{(\sum_i x_i)^2}{N}}{N-1}} \quad , \tag{6}$$

where the x_i values represent the individual measurements and N is the number of x_i values used for a particular Type A component. The standard deviation of the mean is $S_r/N^{½}$, and the total standard deviation of the mean is $[\sum(S_r^2/N)]^{½}$, where the summation is carried out for all Type A components.

All the Type B components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\delta_s$, and zero probability of being outside that region). If the distribution is rectangular, the standard deviation, σ_s, for each Type B component is equal to $\delta_s/3^{½}$ and the total 'standard deviation' is $(\sum\sigma_s^2)^{½}$, where the summation is performed over all Type B components.

The combined uncertainty is determined by combining the Type A and Type B standard deviations in quadrature; the expanded uncertainty is obtained by multiplying this result by a coverage factor of **2**. The expanded uncertainty, U, is then

$$U = 2\sqrt{\sum_s \sigma_s^2 + \sum_r \frac{S_r^2}{N}} \quad . \tag{7}$$

The values used to calculate the NIST expanded uncertainty (shown in Tables 1 through 4) are listed in Table 5. The number of decimal places used in reporting the mean values of the correction factor were determined by expressing the expanded NIST uncertainty to two significant digits.

Type A
Repeatability: This is an uncertainty due to the scatter of data points around the measurement average obtained from three calibration runs on the OFPM being calibrated.

Type B
a. Laser power stability: During the nonlinearity calibration of an OFPM, changes in optical power such as drift or fluctuations can cause a possible error. The power stability is measured during the time interval in which the three measurements are taken. The low power (when an individual shutter is open) is measured before and after the high power

(when both shutters are open). The value for laser stability is found by measuring the drift for each laser source. The slope of the drift (percent per second) is then multiplied by the interval that the three shutters are open (3 s) during an actual nonlinearity calibration. The maximum measured value of the power drift is 0.21 % at 850 nm, and 0.09 % at 1300 nm and 1550 nm. The standard uncertainty for laser stability is $0.21/(2\sqrt{3}) = 0.06$ % at 850 nm, and $0.09/(2\sqrt{3}) = 0.03$ % at 1300 nm and 1550 nm.

b. Polynomial truncation: The conversion function of an OFPM is a least-squares fit to a third-order polynomial. The uncertainty is due to truncation of the polynomial of higher orders. The maximum value of the error is equal to 0.007 %. The standard uncertainty is $0.007/(2\sqrt{3}) = 0.002$ %.

c. Test meter spectral responsivity: This uncertainty is caused by drift of the source wavelength and a drift of the optical spectrum analyzer during each triplet measurement. The size of the uncertainty depends on the absorbing material of the power meter detector. The value is estimated based on the spectral responsivity curves for Si, Ge, and InGaAs detectors. We assume a combined variation for the lasers wavelengths and accuracy of the optical spectrum analyzer of 0.1 nm.

d. Equation approximation: This uncertainty is due to the approximation in the nonlinearity equation. The uncertainty is of second-order in magnitude, i.e., if the nonlinearity is 1 %, then the uncertainty is $(0.01)^2$ or 10^{-4}. This uncertainty depends on the value for the nonlinearity in each case. The maximum uncertainty will be divided by $(2\sqrt{3})$.

e. Polarization: This uncertainty is due to effects caused by changes in polarization of the incident power during each triplet measurement set. This uncertainty is related to polarization dependent loss (PDL) of the nonlinearity system. Polarization uncertainty of the nonlinearity system is assumed to be small because we take a large number of measurements (810 measurements per one power range) and because measurement time scales are short compared to changes in the system polarization state. The PDL of the nonlinearity system was measured using a random-polarization generator. The maximum value of the system PDL is 0.002 dB or 0.05 %. The standard uncertainty is $0.05/(2\sqrt{3}) = 0.014$ %.

Table 5 lists typical measurement uncertainties associated with the nonlinearity calibration of an OFPM. The exact value of these various components can change depending on the particular measurement conditions.

Table 5. Typical nonlinearity measurement uncertainties.

Source	Standard uncertainty (type) (%)
Laser stability	
@ 850 nm	0.06 (B)
@ 1300 & 1550 nm	0.03 (B)
Polynomial truncation	0.002 (B)
Test meter spectral responsivity	
@ 850 nm (Si)	0.004 (B)
@ 850 nm (Ge)	0.014 (B)
@ 850 nm (InGaAs)	0.015 (B)
@ 1300 nm (Ge)	0.004 (B)
@ 1300 nm (InGaAs)	0.003 (B)
@ 1550 nm (Ge)	0.027 (B)
@ 1550 nm (InGaAs)	0.001 (B)
Polarization	0.014 (B)
Equation approximation	0.003 (B)
Repeatability (N = 3)	See Tables 1 through 4 (A)
Typical combined uncertainty	0.05
Typical expanded uncertainty (k = 2)	0.10

OPTICAL POWER METER
Meter's Manufacturer
Model Number, Serial Number
with Sensors
Model Number X, Serial Number 1
Model Number Y, Serial Number 2

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and Technology

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