

Nonlinearity of high-power optical fiber power meters at 1480 nm

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We describe a calibration system that measures the nonlinearity of optical fiber power meters (OFPMs) at a maximum power of 0.6 W and a minimum power of 0.2 mW at 1480 nm. The system is based on the triplet superposition method. This system measures the nonlinearity of OFPMs by using correction factors at different powers; the system is an important tool for characterizing OFPMs at high powers in the S band. The measurement uncertainties, typically better than 0.2%, $k = 2$, associated with the high-power nonlinearity system are also described. © 2006 Optical Society of America

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1. Introduction

With the advent of erbium-doped fiber amplifiers that require high-power pump lasers and semiconductor laser amplifiers, there is a need to measure optical power accurately at higher levels than before.¹ Optical fiber power meters (OFPMs) are now capable of measuring powers exceeding several watts in an optical fiber. Our previous work² uncovered problems with OFPM nonlinearity at 980 nm, a common pump laser wavelength. In this paper we address nonlinearity at another common pump laser 1480 nm.

Usually the OFPM output readings are directly proportional to the optical input power. This proportionality is called linearity, and a departure from this proportionality is defined as nonlinearity. The International Electrotechnical Commission standard IEC 61315 defines optical power meter nonlinearity as the relative difference between the response at an arbitrary power and the response at the reference power³:

$$\text{nl}(P/P_0) = \frac{r(P)}{r(P_0)} - 1, \quad (1)$$

where $r(P) = V/P$ is the response of the meter at optical power P , the subscript 0 indicates the reference

power of a certain range of an OFPM, and V is the reading of the OFPM. Generally, an OFPM has a dynamic range of many decades. An OFPM is designed to switch ranges during optical power measurements. When the OFPM switches from one range to another, it is critical that two neighboring ranges measure the same power. If the readings V at these two ranges for the same input power P are different, then the OFPM has a range discontinuity.

Calibration of an OFPM yields the calibration factor F_c from the OFPM output reading and V at the reference power and establishes traceability to national standards.⁴ The nonlinearity and range discontinuity measurements, together with the calibration factor, provide input optical power P versus output reading V at any given power within the entire dynamic range of the OFPM.

2. Correction Factor for Nonlinearity and Range Discontinuity

Input power P is obtained from the OFPM reading V by

$$P = \frac{V}{F_c \cdot \text{CF}}, \quad (2)$$

where $F_c = V_c/P_c$ is the calibration factor described in Ref. 4, and by use of the polynomial expression

$$\text{CF}[m] = \frac{a_1[c]}{a_1[m]} \times \frac{1 + \sum_{k=2}^n b_k[c]V_c^{k-1}}{1 + \sum_{k=2}^n b_k[m]V^{k-1}}, \quad (3)$$

where CF is a correction factor that is due to nonlin-

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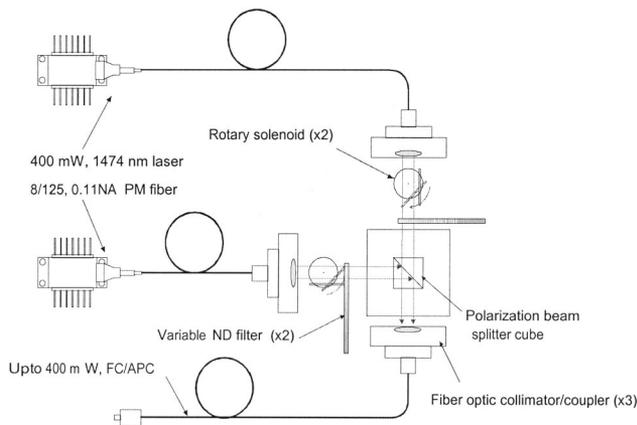


Fig. 1. Measurement system.

earity and range discontinuity, m is a number that corresponds to a specific range of an optical power meter, and subscript c indicates a reference power or the calibration point. $a_1[c]$ is determined by calibration, and the discontinuity coefficients $a_1[m]$ outside range $[c]$ are determined from Eqs. (4) or (5):

$$\frac{a_1[c]}{a_1[m]} = \frac{a_1[c]}{a_1[c+1]} \times \dots \times \frac{a_1[m-1]}{a_1[m]} \quad \text{for } m > c, \quad (4)$$

or

$$\frac{a_1[c]}{a_1[m]} = \frac{1}{\frac{a_1[m]}{a_1[m+1]} \times \dots \times \frac{a_1[c-1]}{a_1[c]}} \quad \text{for } m < c. \quad (5)$$

The coefficients in Eq. (3) 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. (3). Each range of an OFPM has its own correction factor. In Ref. 5 we discussed a low-power nonlinearity system that was designed to calibrate OFPMs up to several milliwatts. The high-power nonlinearity system has some similarities to the low-power counterpart but has some differences as well. We discuss the system in Section 3.

3. Measurement System

The measurement system is based on the triplet superposition method.^{2,5-9} This method relies on the principle that, for a linear OFPM, the sum of OFPM outputs that correspond to inputs from two individual beams should equal the output when the two beams are combined and incident onto the OFPM at the same time. The measurement system is depicted in Fig. 1 and described below.

Each laser is a 1480 nm laser diode in a butterfly

package with an integrated thermoelectric cooler, monitor photodiode, and thermistor. The laser's pigtail is a polarization-maintaining (PM) fiber with a core/cladding size of 8/125 μm and a numerical aperture (NA) of 0.11. The laser diode is driven in constant-power mode with a high-power laser driver that contains an adjustable current limit and a laser-enable feature. The temperature is held constant at 23 $^\circ\text{C}$ by the thermoelectric cooler control module.

The output fiber of the first laser diode is aligned with a high-power collimator that produces a beam diameter of approximately 3 mm. This beam then propagates through a high-power optical shutter. The shutter is a rotary solenoid with a beam blocker mounted onto the shaft. For safety reasons, the beam is blocked when the shutter is in the off position. When the shutter is activated, the beam blocker is removed from the optical path, enabling the beam to pass through.

The beam then passes through a linear, variable neutral-density (ND) filter that is 75 mm in length. The filter density is variable from 0 to approximately 40 dB at 1480 nm. The filter is mounted on a linear translation stage and is driven by a servomotor-encoder combination. The translation stage has its travel limit set at each end by a limit switch. The total beam travel is approximately 60 mm, with a step count of more than 90,000. The translation stage is controlled through an RS-232 port.

The beam then enters the polarization beam-splitter cube. The polarization axis of the beam is oriented to the cube in such a way as to provide the maximum transmission throughput to the high-power output coupler, which utilizes a 105 μm core fiber with a numerical aperture of 0.22. This fiber is routed to the outside of the case via a 3 mm stainless-steel armored cable (for safety) and is terminated with an FC/APC connector.

The second laser transmits, via an identical system, to the polarization beam-splitter cube. The polarization axis of this beam is oriented orthogonally to the beam of the first laser. The polarization beam-splitter cube provides the maximum reflected throughput to the high-power output coupler. The light is then coupled with the first beam into the 105/125 μm , 0.22 NA fiber, which is a normal (not a polarization-maintaining) fiber. The output of each laser at the tip of the fiber is set at approximately 400 mW.

We perform the measurements by taking sets of three power readings from the OFPM: (1) path 1 is open and path 2 is closed, (2) both paths are open, and (3) path 1 is closed and path 2 is open. To provide the OFPM dynamic range, this sequence is then repeated at different powers.

The system is also designed to measure the OFPM range discontinuity (i.e., offsets between ranges). Power readings are taken at the lower-power end of each range and compared with the readings on the higher-power region of the next lower range (if any) at a constant input power. The calculated correction factors result from the OFPM nonlinearity within

Table 1. Nonlinearity Correction Factors for OFPM 1 at 1480 nm

Meter/Scale Range (dBm)	Power Used (mW)	Correction Factor	Standard Deviation (%)	Expanded Uncertainty of CF (%; $k = 2$)
30	600	1.014	0.08	0.16
	500	1.013	0.09	
	200	1.009	0.07	
20	150	1.008	0.06	0.15
	50	1.005	0.06	
	20	1.003	0.07	
10	1.5–20	1.002	0.13	0.16
0	0.15–2	1.000	0.01	0.07

each range, combined with the range discontinuity. This system is similar to the nonlinearity system described in Ref. 2.

The high-power nonlinearity systems described here and in Ref. 2 use two lasers whose center wavelengths are separated by several tenths of a nanometers. Two lasers produce enough power for calibrating high-power OFPMs and to compensate for the insertion loss of the system. In contrast, the low-power nonlinearity system in Ref. 5 uses only one laser, whose radiation is divided into two paths.

4. Results

We performed nonlinearity measurements at 1480 nm on two commercially available OFPMs. Each OFPM consisted of an integrating sphere and an InGaAs detector. The nonlinearity results for two OFPMs are presented in the form of two tables and a figure. Table 1 lists the nonlinearity correction factors for OFPM 1 with the associated uncertainties. The correction factors result from an OFPM nonlinearity within each range, combined with the range discontinuity. Most OFPMs use power ranges in dBm units [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]. Each correction value listed in Tables 1 and 2 is the average of six correction factors (except for the 30 and 20 dBm ranges, which are represented by only three points) found throughout that range. If the nonlinearity variation within one range is not negligible compared with its uncertainty, it is necessary to provide correction factors at each power. Table 1 lists the correction factors and associated uncertainties for three powers for 20 and 30 dBm ranges. It is possible to calculate the uncertainties for these two ranges by averaging the correction factors

Table 2. Nonlinearity Correction Factors for OFPM 2 at 1480 nm

Meter/Scale Range (dBm)	Power Used (mW)	Correction Factor	Standard Deviation (%)	Expanded Uncertainty of CF (%; $k = 2$)
30	150–600	1.002	0.02	0.07
20	15–200	1.001	0.03	0.07
10	1.5–20	1.001	0.05	0.09
0	0.15–2	1.000	0.01	0.07

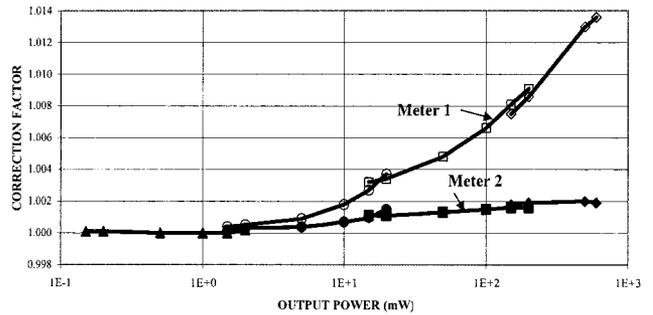


Fig. 2. Correction factors versus output power for two OFPMs at 1480 nm.

for each range. However, the uncertainties when such an approach is used will be larger than that for specific powers in Table 1.

Table 2 lists the nonlinearity correction factors for OFPM number 2 with the associated uncertainties. Because OFPM 2 is more linear than OFPM 1, the correction factors are given for the entire ranges rather than for specific powers.

Figure 2 depicts the correction factors obtained for both high-power OFPMs at 1480 nm. Each data group represents a separate power range setting of the meters. The total nonlinearity (including range discontinuities) of the OFPM 1 is approximately 1.4%, while the total nonlinearity of the OFPM 2 is less than 0.25% for powers from 0.2 mW to 0.6 W. Note that the reference power (where the correction factor is 1) is chosen to be 1 mW. For the OFPMs 1 and 2 the nonlinearity at 1480 nm is smaller than that at 980 nm, a common pump laser wavelength.² A similar spectral nonlinearity behavior was described in Ref. 10.

5. Uncertainty Assessment

In this section we assess the associated uncertainty described in Tables 1 and 2 for both OFPMs. We describe and combine the uncertainty estimates for the National Institute of Standards and Technology’s OFPM nonlinearity and range discontinuity measurements, using the referenced guidelines.¹¹ To establish the uncertainty limits we separated the uncertainty sources into type A, whose magnitudes are obtained statistically from a series of measurements, and type B, whose magnitudes are determined by scientific judgment. The details of the uncertainty assessment can be found in Ref. 5. Table 3 lists typical measurement uncertainties for calibrations of an OFPM based on an InGaAs detector, as follows.

A. Type A

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

B. Type B

(a) **Laser power stability:** During the nonlinearity calibration of an OFPM, changes such as drift

Table 3. Example of Nonlinearity Measurement Uncertainties for an InGaAs OFPM at 1480 nm

Source	Standard Uncertainty (Type) (%) ^a
Laser stability	0.06 (B)
Polynomial truncation	0.002 (B)
Test meter spectral responsivity for InGaAs detector	0.001 (B)
Polarization	0.014 (B)
Repeatability ($N = 3$)	0.07 (A)
Combined uncertainty ($k = 1$)	0.074
Expanded uncertainty ($k = 2$)	0.15

^aSee text for explanation of types.

and fluctuations in optical power can cause an 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 measurement of the drift for the laser.

(b) Polynomial truncation: The response 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 value of the error can be found in Ref. 7.

(c) Test meter spectral responsivity: This uncertainty is caused by a drift of the laser wavelength and the corresponding value of the spectral responsivity for a quantum detector. Typical spectral responsivity slopes (percent per nanometer) for the Ge and InGaAs detectors used in most high-power OFPMs are 0.92 and 0.05, respectively.

(d) 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 of the nonlinearity system.

The standard uncertainty in Table 3 is an estimated standard deviation for each uncertainty component, and the combined uncertainty represents the estimated standard deviation of the nonlinearity and range discontinuity measurements.

6. Conclusions

We have designed and built a nonlinearity system that allows us to obtain correction factors for optical fiber power meters at a maximum power of 0.6 W at 1480 nm. The measurement uncertainties associated with the system are small, and the system is relatively straightforward to implement, which makes this system attractive for calibrating OFPMs at high powers. Our experience has shown that many OFPMs exhibit nonlinear behavior at high powers. Therefore we suggest that OFPM users perform nonlinearity measurements before using OFPMs at high powers.

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