Optical high-power nonlinearity comparison between the National Institute of Standards and Technology and the National Metrology Institute of Japan at 1480 nm

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We compare the results of measurements of the nonlinearity of high-power optical fiber powermeters (OFPMs) by two national metrology institutes (NMIs): the National Institute of Standards and Technology (NIST-USA) and the National Metrology Institute of Japan/National Institute of Advanced Industrial Science and Technology (NMIJ/AIST-Japan) at a wavelength of 1480 nm. The nonlinearity and range discontinuity of a commercial OFPM were measured from 1 mW to 500 mW by use of a superposition method (both laboratories) and from 1 mW to 250 mW by use of a comparison method (NMIJ only). Measurement results showed largest differences of less than 1.6 parts in 10^3, which is within the combined expanded ($k = 2$) uncertainty for both laboratories.

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1. Introduction

Contemporary optical telecommunication systems require transmission of information at higher data rates and optical powers than ever before. Several national metrology institutes (NMIs) have completed comparison of their reference standards at high optical powers [1]. Others studied the nonlinearity of optical fiber powermeters (OFPMs) at 980 nm [2–4] and 1480 nm [3–5]. In our previous work [6], we reported the results of low-power (up to several milliwatts) nonlinearity comparisons between NIST and NMIJ at 1310 and 1550 nm. This paper addresses measurements of nonlinearity and range discontinuity at 1480 nm of a commercial OFPM, which is based on an integrating sphere and an indium gallium arsenide (InGaAs) detector at powers (a) from 1 mW to 500 mW by use of two different versions of the superposition method by the two laboratories and (b) from 1 mW to 250 mW by use of a comparison method by NMIJ only.

The output power reading for a linear OFPM is directly proportional to the optical input power. The departure from this proportionality is defined as nonlinearity. The international standard IEC 61315 defines optical powermeter nonlinearity as the relative difference between the response at an arbitrary power and the response at the reference power [7]:

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

where $r(P)$ is the response of the meter at optical power P and the subscript 0 indicates the reference power of a certain range of an OFPM. Generally, an OFPM has a dynamic range of many decades. An OFPM switches ranges if input optical power is being varied beyond the limit of one measurement range. It is important that two neighboring ranges have the same readings when measuring the same power; if not, then the OFPM is considered to have a range discontinuity.

2. NIST Superposition Measurement System

The NIST measurement system described in detail in [5] is depicted in Fig. 1. The measurement system is based on the triplet superposition method [2–6,8–12]. This method relies on the principle that, for a linear OFPM, the sum of 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 measurements are performed 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 cover the OFPM dynamic range, this sequence is then repeated at different powers. The measurement system is also designed to measure the OFPM range discontinuity. Power readings are 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 any) at constant input power. The calculated correction factors [5] result from the OFPM nonlinearity within each range, combined with the range discontinuity. The high-power nonlinearity systems described here and in [2] use two lasers whose center wavelengths are separated by several tenths of a nanometer. Two lasers are used to produce enough power to calibrate high-power OFPMs and compensate for the insertion loss of the measurement system. In contrast, the low-power nonlinearity system described in [8,11,12] uses only one laser, whose beam is divided into two paths and then recombined at the OFPM input port.

3. NMIJ Superposition Measurement System

The NMIJ superposition measurement system is depicted in Fig. 2. 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 single-mode fiber. The laser diode is driven in constant-current mode with a laboratory-made laser driver that contains an adjustable current control. The appropriate heat sink is equipped for cooling the laser module. The output fibers of the laser diodes are connected to two optical programmable attenuators. The attenuation is variable from 0 to 60 dB at 1480 nm [the attenuators are controlled through an IEEE 488 (GPIB) port]. Each optical power enters a special fiber cable, which has two regular fiber connectors for the optical input and one specially made fiber connector with two fiber cores in a single ferrule for optical output. The output port is terminated with an FC/APC (angled) connector. The maximum output power for each laser is approximately 250 mW; therefore the nonlinearity of the device under test (DUT) powermeter can be measured up to 500 mW. Optical powers through optical switches 1 and 2 are superimposed onto the DUT. By adjusting optical attenuators, the same optical power reading on the DUT via switch 1 or 2 can be obtained. Applying both optical powers through switches 1 and 2 at once, the power readings of the DUT, if linear, will be twice that for individual optical powers. Nonlinearity of the DUT is determined from the ratio of the combined power reading to the sum of individual readings. By varying the optical attenuator setting to change the input power, the nonlinearity correction factor (CF) of the DUT can be measured within a wide dynamic range as follows:

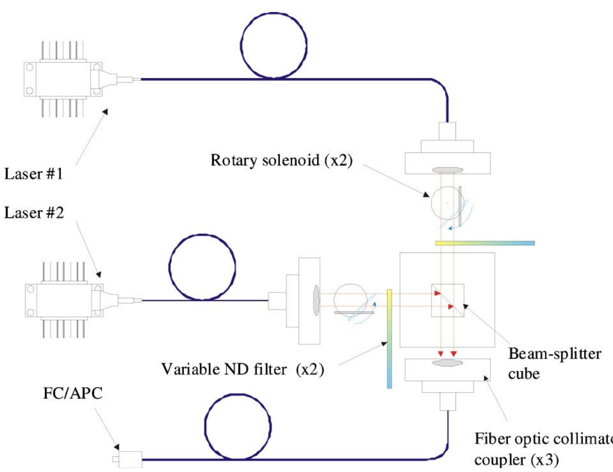

Fig. 1. (Color online) NIST superposition measurement system.

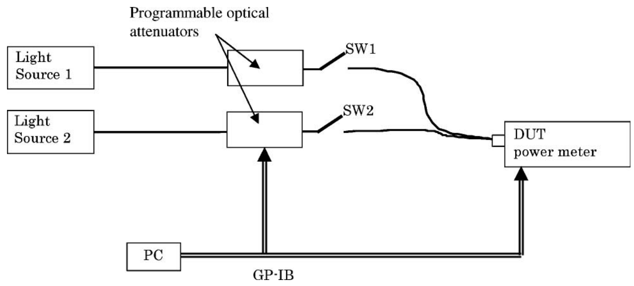

Fig. 2. NMIJ superposition measurement system.

$$\mathrm{CF}_{1+1} = \mathrm{CF}_{1\times 2} = \frac{R(2)}{2\times R(1)}, \quad (1)$$

$$\mathrm{CF}_{2+2} \equiv \frac{R(4)}{2\times R(2)}. \quad (2)$$

Therefore,

$$\mathrm{CF}_{1\times 4} = \frac{R(4)}{4\times R(1)} = \mathrm{CF}_{1+1}\times \mathrm{CF}_{2+2}, \quad (3)$$

where $R(i)$ represents the reading of the DUT by applying the unit power (reference power) i times. CF_{i+j} can be derived directly from each superposition process, and $\mathrm{CF}_{1\times k}$ means nonlinearity at the power for k times of the unit power (reference power).

For exact 10 dB calibration, the unit power reading and reading for four times the unit power are superimposed (in other words, $1+4=5$) to obtain $\mathrm{CF}_{1\times 5}$

first. Thereafter, the 10 dB power ratio can be obtained from "5 + 5" as below:

$$\mathrm{CF}_{1+4} \equiv \frac{R(5)}{R(1)+R(4)} = \frac{R(5)}{R(1)+\mathrm{CF}_{1\times4}\times 4\times R(1)} = \frac{R(5)}{R(1)}\cdot\frac{1}{1+4\mathrm{CF}_{1\times4}}. \quad (4)$$

Therefore,

$$\mathrm{CF}_{1\times5} = \frac{R(5)}{5\times R(1)} = \mathrm{CF}_{1+4}\times\frac{1+4\mathrm{CF}_{1\times4}}{5}, \quad (5)$$

$$\mathrm{CF}_{5+5} \equiv \frac{R(10)}{2\times R(5)}. \quad (6)$$

Therefore,

$$\mathrm{CF}_{1\times10} = \frac{R(10)}{10\times R(1)} = \frac{R(10)}{2\times R(5)}\frac{R(5)}{5\times R(1)} = \mathrm{CF}_{5+5}\times\mathrm{CF}_{1\times5}. \quad (7)$$

Range discontinuity between ranges is also measured, and the ratio of readings of the two adjacent ranges with the same input power is applied to the correction factor CF at that power to extend the correction factor from one range to the next. For example, at 10 mW, the correction factor $\mathrm{CF}_{1\times10}$ (assuming that 1 mW is the reference power) at the 100 mW range is obtained by multiplying $\mathrm{CF}_{1\times10}$ at the 10 mW range with the corresponding range discontinuity ratio at 10 mW.

4. NMIJ Comparison Measurement System

The NMIJ comparison measurement system is depicted in Fig. 3. A single laser and a regular single-mode fiber cable after the attenuator are used. The output port is terminated with an FC/APC connector. The maximum available output power is 250 mW.

By use of this method, the DUT is calibrated by comparing it with a standard optical powermeter [13] whose nonlinearity was measured by the superposition method, as follows:

I. Record the ratio of the standard powermeter readings between 1 mW and each calibration power level, $A_s(k)$, by applying attenuation $A(k)$ of the optical attenuator.

II. Record the ratio of the DUT readings between 1 mW and each calibration power level, $A_T(k)$ by applying the same attenuation $A(k)$ of the optical attenuator.

III. Repeat I (4 times) and II (3 times).

IV. The correction factor due to nonlinearity of DUT, CF_T is calculated as the average of

$$\mathrm{CF}_T = \frac{1}{N}\sum_{k=1}^{N}\frac{A_T(k)}{(A_S(k)+A_S(k+1))/2}\cdot\mathrm{CF}_S \quad (N=3), \quad (8)$$

where CF_s is the correction factor due to the nonlinearity of the standard powermeter. Range discontinuity can be applied in the same way as described in Section 3.

5. Results

We measured nonlinearity and range discontinuity at 1480 nm using a commercially available OFPM, which consists of an integrating sphere and an InGaAs detector. The nonlinearity results are presented in Figs. 4 and 5 and Tables 1 and 2. The correction factors CF result from OFPM nonlinearity within each range, combined with the range discontinuity. We compare the results in Subsection 5.A using the superposition method for both laboratories and in Subsection 5.B using superposition (NIST) and comparison (NMIJ) methods. Both laboratories followed uncertainty guidelines described in [14]. More detailed NIST uncertainty analysis can be found in [5,8,15]. Components of the uncertainty in NMIJ's superposition method are (a) source spectrum bandwidth and wavelength dependence of DUT, (b) source stability, (c) polarization dependence, (d) temperature fluctuation, (e) power level setting, and (f) repeatability. At 500 mW, for example, the relative uncertainty values were (a) 0.008%, (b) 0.049%, (c) 0.008%, (d) 0.009%, (e) 0.018%, and (f) 0.007%. In NMIJ's comparison meth-

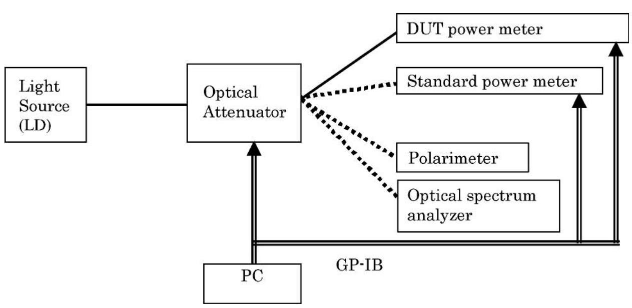

Fig. 3. NMIJ comparison measurement system.

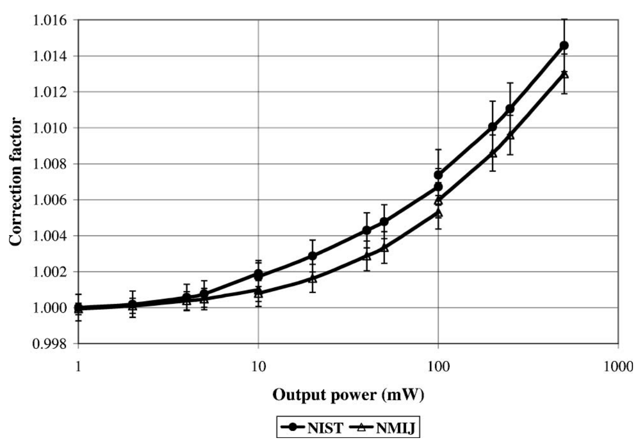

Fig. 4. Measurement results using the superposition method for both laboratories.

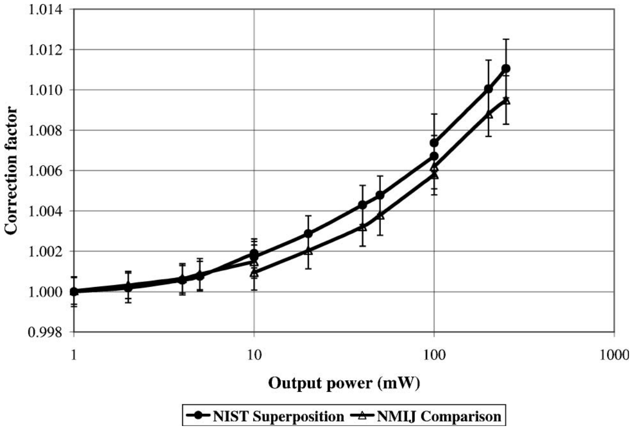

Fig. 5. Measurement results using the NIST superposition and NMIJ comparison methods.

od, the uncertainty of the standard powermeter was also taken into account in addition to those components described above. The combined standard uncertainty for both laboratories is found as a square root of the sum of the squares of each laboratory's standard uncertainty. The combined expanded uncertainty is calculated by multiplying the combined standard uncertainty by a coverage factor of $k = 2$. The measurements at NIST were taken before the equipment was shipped to NMIJ and after the equipment arrived at NIST. Tables 1 and 2 present the average results from those measurements. Most OFPMs use power ranges in dBm units (dBm is not an SI unit, but it is related to a power of 1 mW as $10 \log(x)$, where x is an unknown power in milliwatts). The reference power (where the correction factor is 1) is chosen to be 1 mW for this comparison.

A. Results Using the Superposition Method

In this section we compare the results using the superposition method for both laboratories for powers from 1 mW to 500 mW. Figure 4 depicts the correction factors obtained for the DUT by both laboratories. Each correction factor is shown with the error bars representing associated expanded uncertainties for the participating laboratory. Table 1 shows DUT nonlinearity correction factors with the combined expanded uncertainties. In each power range (except 30 dBm), the nonlinearities are measured at five powers, at 1, 2, 4, 5, and 10 times the lowest measurable power of that range (one tenth of the full range). For example, using the 20 dBm range, the nonlinearity correction factors were measured at the following powers: 10, 20, 40, 50, and 100 mW. The largest relative difference between the nonlinearity correction factors for both laboratories was −1.6 parts in 10^3, which is within the combined expanded uncertainty (1.8 parts in 10^3). For the 20 dBm range at all powers except 10 mW, the relative differences between correction factors are slightly larger (less than 1.5 parts in 10^4) than the combined expanded uncertainties. For the other two ranges (30 dBm and 10 dBm), the relative differences between the nonlinearity correction factors are smaller than the combined expanded uncertainty. A close look at the curves reveals that the differences between the two measurement results are caused mainly by the nonlinearity difference at a single point, 10 mW; otherwise, the agreement of the measurements at other powers is very good.

B. Results Using the NIST Superposition and NMIJ Comparison Methods

In this section we compare the results of superposition (NIST) and comparison (NMIJ) methods for powers from 1 mW to 250 mW. Figure 5 depicts the correction factors obtained for DUT by both laboratories. Each correction factor is shown with the error bars representing expanded uncertainties for the participating laboratory. Table 2 shows nonlinearity correction factors for the DUT with the combined expanded uncertainties. The largest relative difference between the nonlinearity correction factors for both laboratories was −1.5 parts in 10^3, which is within the combined expanded uncertainty (1.9 parts in 10^3). For all three DUT ranges (from 10 dBm through 30 dBm), the relative differences between the nonlinearity correction factors are smaller than the

Table 1. Nonlinearity Results Using the NIST and NMIJ Superposition Methods

Meter Range (dBm)	Output Power (mW)	NIST Average CF	NMIJ Average CF	100× Difference NIST-NMIJ	100× NIST-NMIJ Combined Expanded Uncertainty ($k = 2$)
30	500	1.0146	1.0130	−0.16	0.18
	250	1.0111	1.0096	−0.14	0.18
	200	1.0101	1.0086	−0.14	0.17
	100	1.0074	1.0060	−0.14	0.17
20	100	1.0067	1.0053	−0.141	0.138
	50	1.0048	1.0033	−0.144	0.129
	40	1.0043	1.0029	−0.141	0.128
	20	1.0029	1.0016	−0.124	0.118
	10	1.0017	1.0008	−0.093	0.104
10	10	1.0019	1.0010	−0.090	0.097
	5	1.0008	1.0005	−0.029	0.094
	4	1.0006	1.0004	−0.019	0.089
	2	1.0002	1.0001	−0.009	0.085
	1	1.0000	0.9999	−0.007	0.080

Table 2. Nonlinearity Results Using the NIST Superposition Method and NMIJ Comparison Methods

Meter Range (dBm)	Output Power (mW)	NIST Average CF	NMIJ Average CF	100× Difference NIST-NMIJ	100× NIST-NMIJ Combined Expanded Uncertainty ($k = 2$)
30	250	1.0111	1.0095	−0.15	0.19
	200	1.0101	1.0088	−0.12	0.18
	100	1.0074	1.0062	−0.12	0.18
20	100	1.0067	1.0058	−0.090	0.140
	50	1.0048	1.0038	−0.100	0.140
	40	1.0043	1.00322	−0.107	0.137
	20	1.0029	1.00204	−0.083	0.127
	10	1.0017	1.00095	−0.077	0.115
10	10	1.0019	1.00149	−0.041	0.109
	5	1.0008	1.00087	0.010	0.106
	4	1.0006	1.00066	0.009	0.104
	2	1.0002	1.00033	0.014	0.099
	1	1.0000	1.0000	0.004	0.099

combined expanded uncertainty. Similar to the comparison of the two superposition measurement results, the large difference in nonlinearity and range discontinuity at 10 mW is the main cause of the overall difference (at other powers the agreement between the results of the two different methods of the two laboratories is much better).

6. Conclusion

We have compared the high-power nonlinearity results between NIST and NMIJ laboratories at 1480 nm. The measurement results showed a largest difference of 1.6 parts in 10^3, which is within the combined expanded ($k = 2$) uncertainty for both laboratories. Similar high-power comparisons (e.g., at 980 nm) should be conducted at different laser wavelengths, as suggested in [16].

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