Effective Area and Nonlinear Coefficient Measurements of Single-Mode Fibers: Recent Interlaboratory Comparisons [†]

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Abstract: The National Institute of Standards and Technology (NIST) has recently administered two interlaboratory comparisons, coordinated within the Fiber Optics Committees of the Telecommunications Industry Association (TIA), of measurements on single-mode optical fibers. The first dealt with Effective Area (A_{eff}) but also included Mode-Field Diameter (MFD) measurements; the second concerned Nonlinear Coefficient (n_2/A_{eff}). The A_{eff} comparison included five participants. Standard deviations, per fiber, for all participants' measurements, ranged from 0.4 % to 0.7 % for MFD and from 1.3 % to 3.9 % for A_{eff}. The n_2/A_{eff} comparison included data from six participants. Differences in measurement testsets required different participants to use wide ranges of specimen lengths and input powers. Standard deviations, per fiber, for all participants' measurements of n_2/A_{eff}, ranged from 9.6 % to 18.7 %.

From time to time, the National Institute of Standards and Technology (NIST) administers interlaboratory measurement comparisons (sometimes called round robins) among members of the Telecommunications Industry Association (TIA) or, internationally, among members of the International Electrotechnical Commission (IEC) or the International Telecommunications Union (ITU). Administration of such comparisons by a neutral and noncommercial entity, such as NIST, helps to guarantee and maintain confidentiality among participants and, therefore, encourages participation. Such comparisons are used to quantify agreement among various users of particular standard test procedures, to quantify agreement between measurements made using different test procedures, and/or to establish need for or verify effectiveness of calibration artifacts. Here, we report on two recently-completed single-mode optical-fiber comparisons, one dealing with measurements of Effective Area, as well as Mode-Field Diameter, the other with measurements of Nonlinear Coefficient.

Mode-Field Diameter (MFD) is a measure of the transverse extent of the intensity of the mode guided in a single-mode fiber, corresponding to what one might think of as the spot size. MFD is a key specifiable transmission attribute of single-mode fiber and is crucially important to the coupling efficiency between fibers; the better matched the MFD between two fibers, the more efficiently they can be coupled end-to-end. There is a TIA-published test procedure for measuring MFD **[1]**; it includes one near-field and two far-field measurement methods. If a fiber's transmitted intensity distribution were perfectly Gaussian, then the MFD could be calculated directly, using the $1/e$ or $1/e^2$ points. Real intensity distributions of fibers, though, are not Gaussian, to an extent that varies with fiber type, and MFD is defined, from the far-field intensity distribution, as a ratio of integrals known as the Petermann II definition **[2]**, which has been agreed upon in the TIA and in the international standards bodies. The exact formula depends on the method used; far-field formulas implicitly include a Hankel transform, to convert to near field.

Effective Area (A_{eff}) is a single-mode fiber parameter used in system designs that are prone to effects of the nonlinear refractive index, n_2. A_{eff} is similar to MFD, in that it quantifies "spot size," calculating the cross-sectional area of the near-field intensity distribution of the fiber **[3]**. It is calculated from the same data as MFD, but the calculation is different; in the case of far-field power data, the near-field distribution is determined by a zero-order Bessel function. Again, the exact formula used depends on the

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measurement method. There is a TIA-published test procedure for measuring A_{eff} [4]; it includes the same three (one near-field and two far-field) data-gathering methods as the MFD test procedure. Once again, if a fiber's intensity distribution were perfectly Gaussian, A_{eff} would simply be defined as • $(MFD/2)^2$; for actual fibers, A_{eff} differs from this by a factor that, again, varies with fiber type. The definition of A_{eff} has been agreed upon internationally, within the ITU.

Nonlinear Coefficient, defined as n_2/A_{eff}, where n_2, again, is the nonlinear refractive index, is an indicator of the degree to which nonlinear effects (four-wave mixing, stimulated Raman or Brillouin scattering, etc.) will occur in a fiber with higher propagating powers [3]. n_2/A_{eff} is not currently a specified parameter in any of the standards bodies. Draft test procedures exist for two measurement methods. One, a pulsed technique, referred to as the self-phase modulation technique, is a draft ITU test procedure. The other, the Continuous-Wave Dual-Frequency (CWDF) method, is a draft TIA test procedure that has also been proposed to the ITU.

In the first interlaboratory comparison, A_{eff} and MFD measurements were made by five industry participants (as well as MFD measurements by NIST) on four single-mode fibers; two conventional dispersion-unshifted fibers and two large-A_{eff} fibers made up the test samples. Two participants, plus NIST, used the Direct Far-Field (DFF) Scan method, in which a detector (revolving through a portion of the circumference of a large circle, the center of which is coincident with the exit face of the test fiber) scans across the center of the fiber's far-field radiation pattern, giving a one-dimensional "slice" of the far-field intensity distribution. Three participants used the Variable-Aperture Method in the Far Field (VAMFF). For the VAMFF method, a series of different-diameter circular apertures are inserted in the far field radiation pattern, and the light exiting each given aperture is focused onto a detector; the aperture-transmission functions can then be used to reconstruct the far-field intensity distribution. Measurements were made in parallel; that is, each participant measured two unique specimens of each test fiber. Careful attention was paid to the order in which the specimens were cut from the fiber reels, so any longitudinal variations of A_{eff} or MFD could be accounted for. Such effects were small enough to have negligible impact on overall comparison results. Also, DFF participants made scans across orthogonal cross sections of the far-field pattern of each measurement specimen. Averaging the two orthogonal measurements accounted for any noncircularities in the mode-field radiation patterns; such averages could be more meaningfully compared to VAMFF measurements. All participants used wavelengths within 1.5 nm of 1550 nm.

Table 1 displays measurement spreads, showing overall standard deviations, calculated using all participants' average measured values, for each comparison fiber. These standard deviations ranged from 0.4 % to 0.7 % for MFD and from 1.3 % to 3.9 % for A_{eff}. Figure 1 shows MFD data, as relative offsets from NIST-measured values. Figure 2 is a similar plot for A_{eff} data, except offsets are relative to overall average values (NIST did not measure A_{eff}). Error bars represent the standard deviation of all measurements made by a given participant on each test fiber. The error bars do not necessarily represent participants' repeatabilities, since measurements were made on more than one specimen of each test fiber and, for DFF participants, across orthogonal orientations of each fiber end. There are some definite systematic components to participants' data offsets, for both MFD and A_{eff}, so agreement could be improved with better calibration of measurement test sets. NIST has produced a calibration artifact, referred to as a Standard Reference Material (SRM), for MFD [5]. NIST MFD measurements have a well-characterized uncertainty (two standard deviations) of ±30 nm (or nominally 0.3 %) for standard dispersion-unshifted fibers [6]. Participants' MFD measurements were nearly always lower than NIST MFD values. We believe this is accounted for by the fact that NIST carefully corrects MFD data for test-set noise floor (usable dynamic range), which affects measured MFD values as if there were scattered light in the tails of the far-field intensity distribution. Following the current TIA test procedure, in the presence of a significant noise floor or scattered light, without carefully making such a correction, will always result in a calculated MFD that is too low. As of this writing, the TIA is in the midst of updating the MFD test procedure, to give better guidance on this and several other topics. Similar adjustments are also being discussed for the A_{eff} test procedure; these may help account for the large differences in A_{eff} measurement spreads between fibers in this comparison (from table 1 or figure 2, see, for example, the difference in spreads between fibers C and D, both large-A_{eff} fibers).

The second interlaboratory comparison dealt with measurements of n_2/A_{eff}. Data sets were submitted from six industry participants, five who used the CWDF method and one who used the pulsed method. Both methods induce self-phase modulation in the test fiber. A linear fit is made to a plot of nonlinear phase shift versus power, and the slope of the fitted line is directly proportional to n_2/A_{eff}. Each participant measured one specimen of each of four fibers: two dispersion-unshifted, one dispersion-shifted, and one dispersion-compensating. Specimen lengths varied greatly between participants (and even between particular fibers for each given participant -- lengths ranged from roughly 30 m to over 1.5 km); specified transmission parameters, such as chromatic dispersion and attenuation, of the particular fibers and differences between participants' test sets (available input powers, etc.) necessitated different optimal lengths. Fiber suppliers provided values for attenuation, chromatic dispersion, and dispersion slope, so participants did not need to measure these quantities and so relative uncertainties in such measurements would not affect the n_2/A_{eff} results. (A_{eff} values were also provided, so that n_2 itself could be reported without being affected by A_{eff} measurement uncertainties. n_2 results, however, essentially mirrored n_2/A_{eff} results and, therefore, are not presented in this work.) One participant used wavelengths nominally at 1560 nm; all others typically used wavelengths within roughly 2 nm of 1550 nm. Wavelength enters the calculation for n_2/A_{eff} in a few places, but rough numerical estimates indicate that even a difference of 10 nm in wavelength should not change a value of n_2/A_{eff} by more than about 1 %. Furthermore, examination of the comparison data revealed no obvious systematic n_2/A_{eff} differences that correlated with differences in wavelength. CWDF participants used very similar dual-wavelength separations, ranging from 0.28 nm to 0.4 nm. There were differences of roughly an order of magnitude between input powers used by different participants; there were also large differences in the ranges of powers used by different participants. Such differences are determined largely by each test-set/fiber-under-test combination; the lower power limit is determined by the threshold of measurable self-phase modulation, while the upper power limit (for the CWDF method, for example) is determined by the onset threshold of stimulated Brillouin scattering. Clearly, the precision of n_2/A_{eff} determination, since it is based on a linear fit to measured data, improves with a larger number of data pairs and with a greater range of powers, in accordance with well-known statistics of linear regressions. However, in the data of this comparison, there was, again, no obvious or systematic correlation between n_2/A_{eff} differences and power-level or power-range differences.

Results identify fibers with the letters $A-D$. Though identified by the same letters, these are not the same four fibers used in the comparison of A_{eff} and MFD measurements. Likewise, participating laboratories are identified by the numbers $1-6$. These numbers do not necessarily correspond to participant numbers from the other comparison. Table 2 displays measurement spreads, showing overall standard deviations, calculated using all participants' average measured values of n_2/A_{eff}, for each comparison fiber. These standard deviations ranged from 9.6 % to 18.7 %. Figure 3 plots the n_2/A_{eff} comparison data, as relative offsets from overall average values. Error bars represent the standard deviation of repeated measurements (typically three) by a given participant on each test fiber. Spreads and, hence, interlaboratory differences were relatively large. There were definite systematic components to some participants' data offsets; others' offsets were much more random, though, from fiber to fiber. Such spreads are not surprising for relatively new measurements, using early drafts of test procedures, but improvement will be necessary if n_2/A_{eff} is to become a commonly specified parameter. Some improvement might be expected from modifying the test procedures, possibly to be more prescriptive about test sets or to give better guidance on such things as range and number of powers. The primary purpose of this comparison was to evaluate and compare the two measurement methods. With only one set of pulsed data, a conclusive comparison could not be made. The one pulsed set displayed very good repeatability and tracked the overall average values well, although these averages, given the small number of data, could change significantly with the addition of even one more data set and, therefore, are not necessarily accurate predictors of actual values. With five CWDF data sets, we probably have a fairly good indicator of the performance of that method, as currently written. It is encouraging that the pulsed-method data were well-contained within the spreads of the CWDF data, indicating that there are no gross systematic differences between measurements made by the two methods, but, again, more pulsed data would be necessary for this to be conclusive.

Table 1. Spreads, per fiber, for MFD and A_{eff} measurements. Overall standard deviations, calculated from all participants' average reported values, are shown, both as actual values and as percentages of overall averages.

Fiber	Overall standard deviations	
	Mode-Field Diameter, µm	**Effective Area, µm²**
$A_{(STD)}$	0.059 (0.6 %)	2.2 (3.0 %)
$B_{(STD)}$	0.071 (0.7 %)	2.2 (2.7 %)
$C_{(LG\text{-}EFF\text{-}AREA)}$	0.040 (0.4 %)	0.9 (1.3 %)
$D_{(LG\text{-}EFF\text{-}AREA)}$	0.066 (0.7 %)	2.4 (3.9 %)

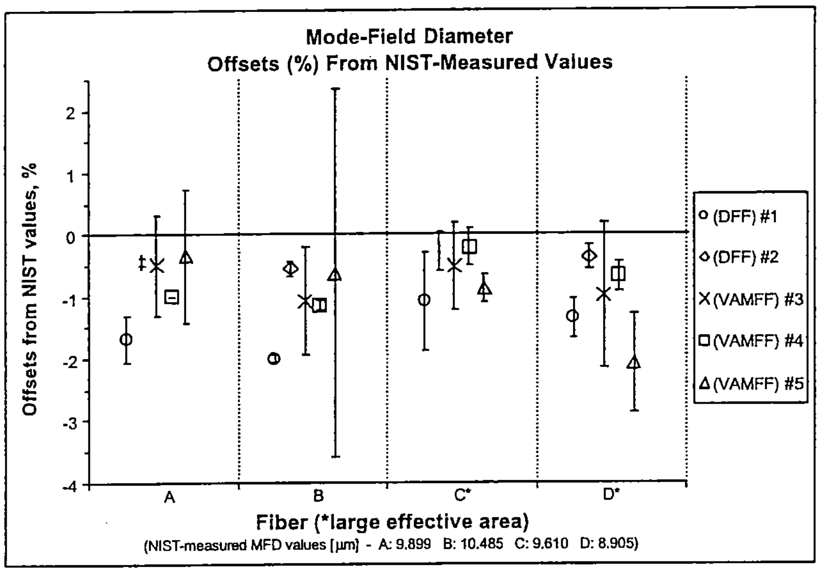

Figure 1. Participants' measurements of MFD, relative to NIST-measured values. Error bars represent standard deviations for multiple measurements on each test fiber, including measurements on more than one specimen of each fiber and DFF scans across orthogonal cross-sections.

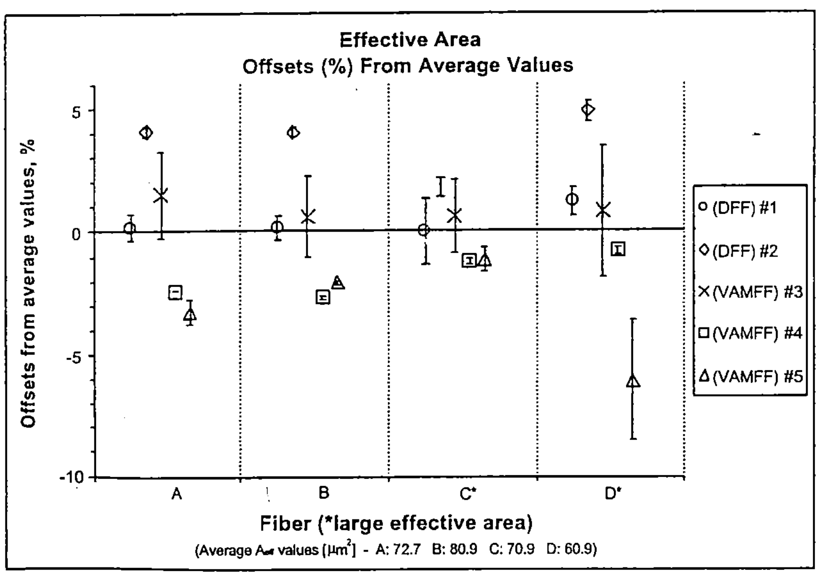

Figure 2. Participants' measurements of A_{eff}, relative to overall average values (NIST did not measure A_{eff}). Error bars represent standard deviations for multiple measurements on each test fiber, including measurements on more than one specimen of each fiber and DFF scans across orthogonal cross-sections.

Table 2. Spreads, per fiber, for n_2/A_{eff} measurements. Overall standard deviations, calculated from all participants' average reported values, are shown, both as actual values and as percentages of overall averages.

Fiber	Overall standard deviations
	Nonlinear Coefficient (n_2/A_{eff}), $\cdot 10^{-10}$ W^{-1}
$A_{(D.\ Unshifted)}$	0.50 (18.7 %)
$B_{(D.\ Shifted)}$	0.60 (13.9 %)
$C_{(D.\ Compens.)}$	1.99 (14.8 %)
$D_{(D.\ Unshifted)}$	0.31 (9.6 %)

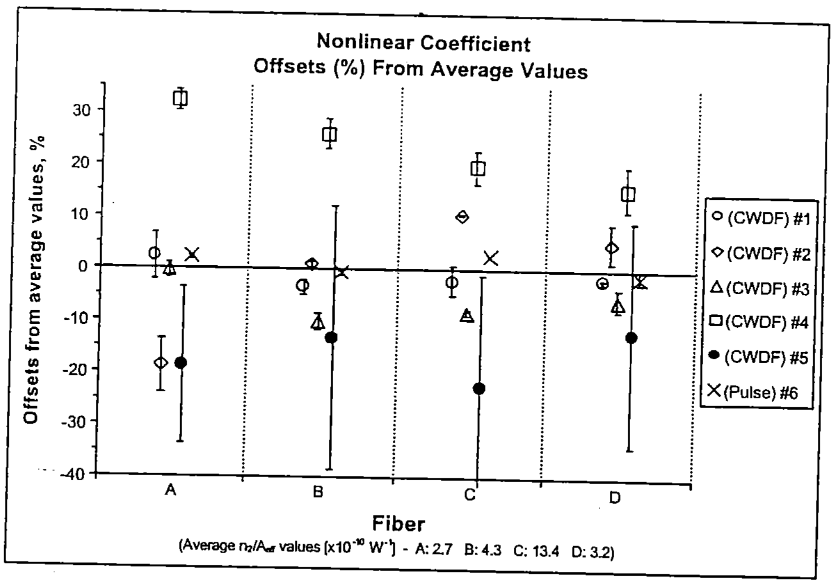

Figure 3. Participants' measurements of n_2/A_{eff}, relative to overall average values. Error bars represent standard deviations for repeated measurements (typically three) on each test fiber specimen.

We thank laboratories that participated or provided fibers: Corning Incorporated, EXFO, GN Nettest, Imperial College, INO, Lucent Technologies, Lucent Technologies Denmark A/S, SpecTran Corporation, Telcordia Technologies, Tyco Submarine Systems Ltd. We especially thank Bill Gardner, of Lucent Technologies, and Tom Hanson, of Corning Incorporated, for designing the nonlinear-coefficient comparison, and Roger Bighouse, of Corning Incorporated, for leading the TIA task group that examined comparison-related modifications to TIA test procedures for mode-field diameter and effective area.

References:

1. TIA/EIA-455-191 (Fiberoptics Test Procedure FOTP-191), "Measurement of mode field diameter of single-mode optical fiber," Telecommunications Industry Association, 2500 Wilson Blvd., Suite 300, Arlington, VA 22201.
2. K. Petermann, "Constraints for fundamental-mode spot size for broadband dispersion-compensated single-mode fibers," *Electron. Lett.*, vol. 19, pp. 712-714, 1983; C. Pask, "Physical interpretation of Petermann's strange spot size for single-mode fibers," *Electon. Lett.*, vol. 20, pp. 144-145, 1984.
3. G. Agrawal, *Nonlinear Fiber Optics*, Academic Press, Inc., San Diego, CA, 1989. (Chap. 2)
4. TIA/EIA-455-132 (Fiberoptics Test Procedure FOTP-132), "Measurement of the effective area of single-mode optical fiber," Telecommunications Industry Association, 2500 Wilson Blvd., Suite 300, Arlington, VA 22201.
5. National Institute of Standards and Technology, Standard Reference Material Program, Bldg. 2, Rm. 204, Gaithersburg, MD 20899; (301) 975-6776. Refer to SRM 2513, Mode-Field Diameter Standard.
6. M. Young, "Mode-field diameter of single-mode optical fiber by far-field scanning," *Appl. Opt.*, vol. 37, pp. 5605-5619, 1998. (Addendum in *Appl. Opt.*, vol. 37, p. 8361, 1998.)