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A Comparison of Far-Field Methods for Determining Mode Field Diameter of Single-Mode Fibers Using Both Gaussian and Petermann Definitions

T. J. Drapela
D. L. Franzen
A. H. Cherin
R. J. Smith

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A Comparison of Far-Field Methods for Determining Mode Field Diameter of Single-Mode Fibers Using Both Gaussian and Petermann Definitions

T. J. DRAPELA, D. L. FRANZEN, MEMBER, IEEE, A. H. CHERIN, SENIOR MEMBER, IEEE, AND R. J. SMITH

Abstract—An interlaboratory comparison of far-field measurement methods to determine mode field diameter of single-mode fibers was conducted among members of the Electronic Industries Association. Measurements were made on dispersion unshifted and shifted fibers at 1300 and 1550 nm. Results were calculated using both Petermann and Gaussian definitions. The Petermann definition gave better agreement than the Gaussian in all cases. A systematic offset of 0.52 μm was observed between methods when applied to dispersion shifted fibers. Such an offset may be caused by limited angular collection.

I. INTRODUCTION

MODE FIELD diameter (MFD) is an important parameter in the characterization of single-mode fiber. A mismatch in MFD, for example, represents a source of intrinsic joint loss. For simplicity, the more common measurement methods are based on the acquisition of far-field radiation patterns. The two most widely used are the one-dimensional far-field scan (FF) and the variable aperture in the far field (VAFF) [1], [2]. Both methods may be implemented using either a Gaussian or Petermann 2 definition of MFD [3]–[5]. The intent of this work is to examine measurement reproducibility and agreement when both methods are applied to various classes of single-mode fiber. This evaluation was accomplished through an interlaboratory comparison conducted by the National Institute of Standards and Technology in cooperation with the Electronic Industries Association (EIA). Participants in the comparison include most of the major fiber and cable manufacturers in North America.

A previous interlaboratory comparison assumed only a Gaussian mode field distribution and used dispersion unshifted fibers [6]. The various methods exhibited good agreement at 1300 nm (0.15 μm, one standard deviation). At 1550 nm, however, an average offset of 0.7 μm was observed between FF and VAFF methods. Those results were not surprising, since the Gaussian assumption is more accurate close to the cutoff wavelength, which is near 1300 nm for this class of fiber.

In an attempt to reconcile measurement offsets, Anderson and Kilmer have shown that the Petermann 2 definition of MFD gives good agreement among various measurement methods, even in those cases where the mode profiles are not approximately Gaussian [7]. Moreover, the definition gives the best prediction of splice loss when mode profiles deviate from Gaussian [8].

II. COMPARISON FIBERS AND MEASUREMENT PROCEDURES

Six single-mode fibers, provided by five different manufacturers, were measured in this comparison. The fibers, numbered 1 through 6, are briefly described in Table I. Two of the fibers (3 and 5) are dispersion shifted, whereas the remaining four are dispersion unshifted.

Typical experimental apparatus for implementing the FF method is shown in Fig. 1.[1] The light source for this method is typically a laser diode. The source is coupled to the fiber under test, and a one-dimensional scan of the exit radiation pattern is made by rotating an apertured detector in the far field. To obtain Gaussian MFD, the relative angular intensity distribution

$$P_1(\Theta) = P_0 e^{-2(\Theta/\Theta_0)^2} \tag{1}$$

is fitted to the experimentally acquired data. The fitting criterion, to obtain Θ_0, is not arbitrary but chosen to maximize a launch efficiency integral [1]. Gaussian MFD is then calculated as

$$\frac{2\lambda}{\pi \tan \Theta_0} \tag{2}$$

where λ is the wavelength. The Petermann MFD is

$$\frac{\sqrt{2}\lambda}{\pi}\left[\frac{\int_0^\infty P_2(\Theta)\sin\Theta\cos\Theta\,d\Theta}{\int_0^\infty P_2(\Theta)\sin^3\Theta\cos\Theta\,d\Theta}\right]^{1/2} \tag{3}$$

where $P_2(\Theta)$ is the measured far-field intensity at angle Θ. Unlike the Gaussian definition, it does not assume a

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T. J. Drapela and D. L. Franzen are with the National Institute of Standards and Technology, Boulder, CO 80303.

A. H. Cherin and R. J. Smith are with AT&T, Norcross, GA 30071.

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[1] The FF measurement conditions closely followed the recommendations of EIA fiber optic test procedure (FOTP) 164.

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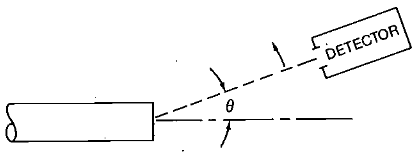

Fig. 1. FF method MFD obtained from a one-dimensional angular scan of the far-field radiation pattern.

TABLE I
DESCRIPTION OF THE COMPARISON FIBERS

Fiber	Dispersion Class	Index Profile
1	Unshifted	Step, Depressed Cladding
2	Unshifted	Step, Depressed Cladding
3	Shifted	Triangular, Depressed Cladding
4	Unshifted	Step, Matched Cladding
5	Shifted	Triangular w/Concentric Ring, Matched Cladding
6	Unshifted	Step

specific functional dependence for the far-field distribution.

A typical experimental apparatus for implementing the VAFF method is shown in Fig. 2.[2] The source generally consists of a tungsten lamp combined with a monochromator or interference filter. The power passing through a series of far-field apertures is measured. There are typically 12 to 20 apertures, covering a fairly broad range of sizes, typically 0.02 to 0.25 NA, but possibly up to 0.5 NA for fibers with smaller MFD's (larger far-field patterns). The distance between fiber and aperture wheel remains fixed during the measurement. Gaussian MFD is calculated by minimizing the mean squared error E^2 given by

$$E^2 = \sum_i \left[P_3(\Theta_i) - P_{3m}\left(1 - e^{-m\tan^2(\Theta_i)}\right)\right]^2 \qquad (4)$$

where $P_3(\Theta_i)$ is the power transmitted through aperture i, Θ_i is the half-angle subtended by aperture i, P_{3m} is the best-fit value of maximum power, and m is a dimensionless parameter adjusted in the fit. Gaussian MFD is then given by

$$\frac{\lambda}{\pi}\sqrt{2m}. \qquad (5)$$

A specific VAFF equation for Petermann MFD was not given. Participants instead performed the calculation directly from the basic definition, using their usual laboratory method [4].

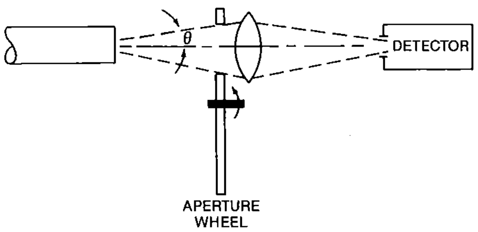

Fig. 2. VAFF method MFD obtained by measuring the relative powers passing through a series of far-field apertures.

There were several measurement conditions common to both FF and VAFF methods. The test fiber length was 2.0 m ± 0.2 m for all measurements. Possible second-order mode power was stripped out through the use of a single 50-mm diameter loop placed in the test length. Cladding mode strippers were also used, when necessary, to remove cladding light.

III. RESULTS

MFD values reported by participants are the average of two measurements. New fiber ends were prepared for each measurement. Slight corrections have been made to reported values, to account for differences in source wavelength. The number of reported values for each fiber, wavelength, and MFD definition varies, because some participants did not carry out all possible combinations. Table II gives the one standard deviation precision claimed by participants for measurements with their test sets.

Results of the comparison naturally group into three fiber and wavelength categories: 1300-nm dispersion unshifted, 1550-nm dispersion unshifted, and dispersion shifted (both wavelengths). This categorization is supported by examining the average offsets between the FF and VAFF methods. For all fibers in any one category, the relative offsets are approximately the same and are given in Table III. For all three categories, the offsets for the Petermann definition are less than those for the Gaussian.

For dispersion unshifted fibers at 1300 nm, the Gaussian results are comparable to the previous interlaboratory comparison [6]. The overall standard deviation is 0.17 μm, with an offset of 0.28 μm between average FF and VAFF results. Petermann results improved upon this, with an offset of only 0.04 μm and an overall one standard deviation of 0.11 μm. Fig. 3 gives MFD results for a typical fiber in this category.

For the same fibers at 1550 nm, the Gaussian definition led to substantial offsets between the FF and VAFF methods, again in agreement with the previous interlaboratory comparison. The average offset is 0.59 μm, and the standard deviation is 0.32 μm. The Petermann definition improved greatly on this, giving an average offset of only 0.05 μm, with a standard deviation of 0.11 μm. Fig. 4 shows MFD results for a typical fiber in this category.

For dispersion shifted fibers, the Gaussian definition gave the largest offsets of the entire comparison. The Pe-

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[2] The VAFF measurement conditions closely followed the recommendations of EIA FOTP 167.

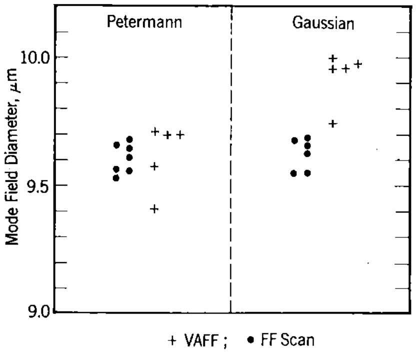

Fig. 3. Typical comparison result for a dispersion unshifted fiber at 1300 nm (fiber 4).

TABLE II
REPORTED PARTICIPANT MEASUREMENT PRECISION, ONE STANDARD DEVIATION

	Petermann, µm		Gaussian, µm
		FF	
	0.007		0.007
	0.1		0.1
	0.02		0.02
	0.02		0.02
	0.03		0.03
	0.02		0.02
	0.05		0.05
Ave:	0.035	Ave:	0.035
		VAFF	
	0.13		0.04
	0.04		0.02
	0.01		0.01
	0.05		0.05
	0.07		0.04
Ave:	0.06	Ave:	0.032

TABLE III
AVERAGE OFFSETS BETWEEN VAFF AND FF MEASUREMENTS, FOR PETERMANN AND GAUSSIAN DEFINITIONS

Category	Offset Between VAFF and FF Methods, µm (Ave. VAFF − Ave. FF)	
	Petermann	Gaussian
1300 nm Dispersion Unshifted	0.04	0.28
1550 nm Dispersion Unshifted	0.05	0.59
1300&1550nm Dispersion Shifted	0.52	0.92

termann definition gave better agreement, but there were still significant offsets. A typical example for this category is shown in Fig. 5. The standard deviation is 0.5 µm for Gaussian, compared to 0.35 µm for Petermann. Average offsets between FF and VAFF methods are 0.92 µm for Gaussian and 0.52 µm for Petermann.

The dispersion shifted Petermann results of one VAFF participant were consistently within the range of FF Petermann results. This participant took special care to construct a VAFF system with uniform collection out to large numerical apertures (NA's). We suspect that the large

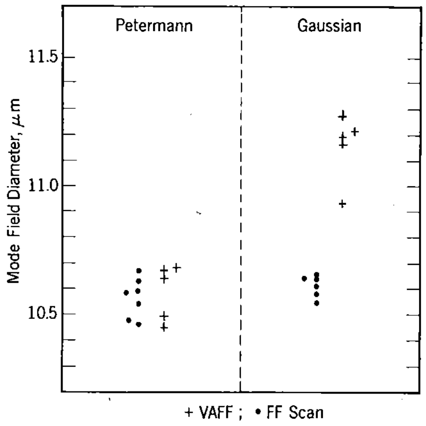

Fig. 4. Typical comparison result for a dispersion unshifted fiber at 1550 nm (fiber 2).

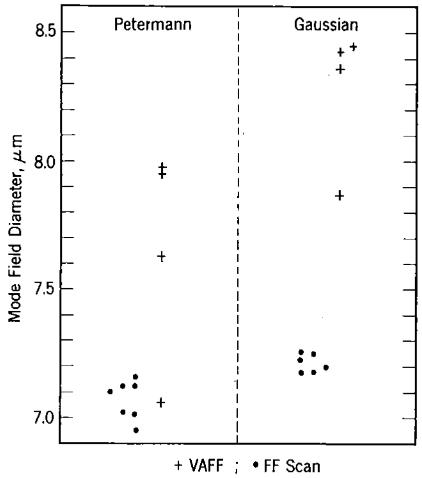

Fig. 5. Typical comparison result for a dispersion shifted fiber at 1550 nm. One VAFF participant was consistently within the range of FF method Petermann MFD's (fiber 3).

VAFF/FF offsets are related to the small MFD's of dispersion shifted fibers. Smaller MFD's mean more power at larger angles in the far field. If the detector and associated optics of a VAFF system do not have sufficiently uniform collection for large enough NA, the measured far-field pattern will be truncated; this translates into a larger measured MFD [9].

The effect of angular truncation was therefore further studied. Measurements on dispersion shifted fibers were more readily influenced because of the larger radiation angles. Fig. 6 gives the experimentally observed increase in FF method MFD when the maximum scan angle was decreased from 24°. For both of the dispersion shifted fibers, an increase of 0.04 µm was observed in Petermann MFD when the maximum scan angle was reduced to 20°; below 20°, the difference rapidly increased. Typical results for one of the unshifted fibers are also shown in Fig. 6. For dispersion unshifted fibers 2, 4, and 6, an 18° scan assured a Petermann MFD within 0.02 µm of asymptotic values. For fiber 1, a scan angle of 22° was necessary. Gaussian MFD's more rapidly approached asymptotic

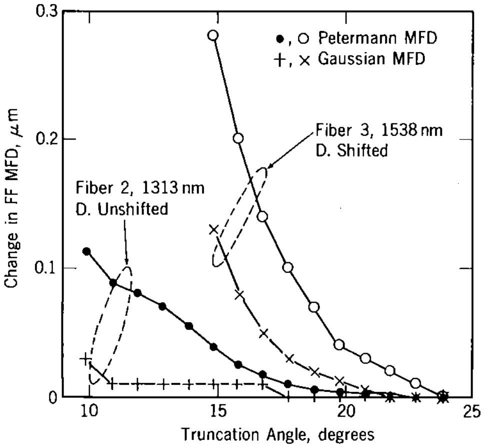

Fig. 6. Change in FF method MFD with respect to 24° scan value when scan is truncated. Gaussian MFD's more rapidly approach an asymptotic value.

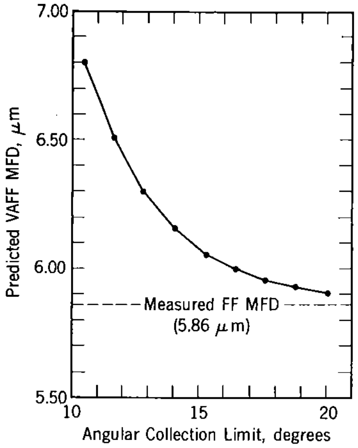

Fig. 7. VAFF method MFD simulated by integrating results of an experimental FF scan. For large collection angle ability, VAFF MFD approaches 5.86 μm, which is the result of the FF measurement. Seventeen apertures, dispersion shifted fiber 3; 1315 nm.

values. This is a consequence of the quickly decaying Gaussian function and the curve fitting criterion.

Next, we examined the effect of angular truncation on the VAFF method. A radiation pattern from a typical FF measurement was integrated to obtain the relative power collected in various cone angles. These data were then used to simulate a measurement by the VAFF method. The offset between the measured MFD from the FF method and the predicted VAFF MFD is given in Fig. 7, for varying amounts of VAFF method angular truncation. Results are for a dispersion shifted fiber at 1300 nm. This case gives the smallest MFD and subsequently largest power at large far-field angles. This truncation does indeed have a pronounced effect on the predicted VAFF results and, in the absence of truncation, the predicted VAFF result differs by only 0.04 μm from the FF result. We encourage further studies on actual VAFF measurements to determine the effect of limiting the collection optics.

In summary, the Petermann definition gave better agreement between VAFF and FF methods than the Gaussian definition, for all classes of fiber and for all wavelengths examined. Agreement for the Petermann definition was adequate for dispersion unshifted fibers at both 1300 and 1550 nm, but in this comparison, the agreement was not adequate for dispersion shifted fibers. This behavior is probably caused by limited angular collection for VAFF measurements rather than by problems with the basic definition.

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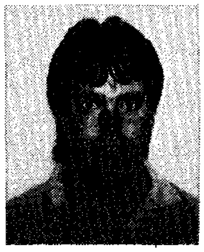

Timothy J. Drapela was born in Denver, CO, in 1962. He received the B. S. degree in physics and computer science from Colorado State University, Fort Collins, in 1984 and the M. S. degree in applied physics from Stanford University, Stanford, CA, in 1987.

He has worked for the Optical Electronic Metrology Group within the Electromagnetic Technology Division of the National Institute of Standards and Technology (formerly the National Bureau of Standards) in Boulder, CO, since 1982, in the areas of laser power and energy measurements and, since 1987, single-mode fiber characterization.

Mr. Drapela is a member of the Optical Society of America.

*

Douglas L. Franzen (S'64–M'66) was born in Minneapolis, MN, in 1942. He attended the University of Minnesota, Minneapolis, where he received the B.S., M.S.E.E., and Ph.D. degrees in electrical engineering in 1964, 1966, and 1970, respectively, with partial support from an NSF grant.

From 1970 to 1972 he was an NRC/NBS postdoctoral Research Fellow in the Quantum Electronics Division at the National Bureau of Standards, Boulder, CO, where he performed some of the early work on continuous laser sustained plasmas. Since then he has been with NBS where he has developed NBS standard instruments for high power laser calorimetry and has shared in some original work on sputtered metal vapor ion lasers. His most recent interests include optical-fiber waveguide metrology and associated technologies. Currently he is a Chairman of an EIA committee on the interlaboratory testing of optical-fiber measurement procedures, and an organizer of the biennial NBS Symposium on Optical Fiber Measurements.

Dr. Franzen is a member of the Optical Society of America. He was awarded the Department of Commerce bronze and silver medals for his efforts in optical-fiber measurements. He also received a Nippon Telegraph and Telephone Directors Award for his work in high-speed lightwave measurements.

Allen H. Cherin (S'60–M'62–SM'84) received the B.E.E. degree in 1961 from the City College of New York, the M.S.E.E. degree in 1965 from the University of Vermont, Burlington, and the Ph.D. degree in electrical engineering in 1971 from the University of Pennsylvania, Philadelphia.

He joined AT&T Bell Laboratories in 1965. He is currently engaged in standards and measurements related to optical fibers and optical fiber systems. He is the author of the textbook *An Introduction to Optical Fibers* (McGraw-Hill).

Dr. Cherin is a member of the Optical Society of America.

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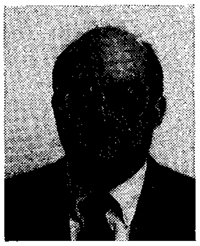

R. J. Smith received the B.S.E.E degree from the Georgia Institute of Technology, Atlanta, in 1969.

In 1980 he joined AT&T Network Systems, Norcross, GA and since then has worked in the area of optical fiber measurements and specifications. His current interests include measurements standards and product specifications.