National Institute of Standards & Technology

Certificate

Standard Reference Material® 2513

Mode-Field Diameter of Single-Mode Fiber

Serial No.:

This Standard Reference Material (SRM) is intended for calibrating systems that use the direct far-field scanning method for measuring the mode-field diameter of a single-mode optical fiber at 1.31 µm and 1.55 µm. The SRM unit includes a short length of bare fiber in an aluminum housing. The end of the fiber has been cleaved carefully so that scattering will be minimal. This SRM was measured individually and bears a serial number. The certified mode-field diameters at two wavelengths for the SRM, given in Table 1, were determined by the direct far-field method as specified by the Telecommunications Industry Association (TIA) [1]. See section entitled Determination of Mode-Field Diameters.

The SRM also includes a 3.5 inch floppy disk that contains raw data for the measured power as a function of angle. These data may be useful for calculating the effective area of the fiber core as well.

Table 1. Certified Mode-Field Diameters

Wavelength (µm)	Mode-Field Diameter (µm)	Uncertainty (µm)
1.31		0.030
1.55		0.030

Expiration of Certification: The certification of this SRM is valid indefinitely within the measurement uncertainties specified, provided that the SRM is used in accordance with the instructions given in this certificate. However, the certification will be nullified if the SRM is damaged or modified.

Maintenance of SRM Certification: NIST will monitor representative samples of this SRM over the period of its certification. If substantive changes occur that affect the certification, NIST will notify the purchaser. Return of the attached registration card will facilitate notification.

The technical direction and physical measurements leading to certification were provided by M. Young with the assistance of T. Drapela of the NIST Optoelectronics Division. The subcommittee that examined and approved the SRM was chaired by K. Rochford of the NIST Optoelectronics Division. R. Wittman of the NIST Radio Frequency Technology Division helped with the theory, and A. Hallam of PK Technology and B. Alpert of the NIST Mathematical and Computational Sciences Division helped with the calculations.

Statistical consultation and guidance on the uncertainty analysis for this SRM were provided by J. Wang of the NIST Statistical Engineering Division and B. Taylor of the NIST Physics Laboratory.

The support aspects involved in the preparation, certification, and issuance of this SRM were coordinated through the NIST Standard Reference Materials Program by J.W.L. Thomas.

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Source of Material: The SRM housing was produced by Larson Engineering, Boulder, CO, and TJZ Precision Machining, Boulder, CO, based on design specifications provided by PK Technology, Beaverton, OR. The fiber was provided by B. Harpster, S. Nipple, and T. Watkins, Corning, Inc., Corning, NY. Ferrules were provided by J. Crittenden and A. Golike of Coors Ceramics, Grand Junction, CO.

Description of SRM: The specimen in the aluminum housing is a single-mode fiber that has been chosen to minimize fluctuations of mode-field diameter with length. The aluminum housings are marked so that the fiber may be held at different angular orientations. The data have been gathered with the flat facet of the brass barrel parallel to the plane of the scan. The polarization of the light at the end of the fiber was not controlled.

Determination of Mode-Field Diameter: The mode-field diameter was measured by the direct far-field method as specified by the TIA. Specifically, the far-field diffraction pattern of the fiber was scanned from −26° to 26°, and the mode-field diameter was calculated according to the formula

$$2w_0 = (\lambda / \pi)\ [2 \int I(\theta) \sin\theta \cos\theta \, d\theta \,/ \int I(\theta) \sin^3\theta \cos\theta \, d\theta\,]^{1/2} \qquad (1)$$

where w_0 is the mode-field radius, λ is the wavelength, and $I(\theta)$ is optical intensity as a function of angle θ. The obliquity factor in Equation (1) is ignored [1].

Determination of Uncertainties: The expanded uncertainty of the certified mode-field diameter values was determined from the combined standard uncertainty of the components of uncertainty and a coverage factor of $k = 2$. Uncertainties were calculated by adding variances, that is, by adding the components of uncertainty in quadrature. Most of the components of uncertainty were calculated or estimated; their distributions were assumed to be rectangular. The optical spectrum analyzer displayed a diurnal variation of its calibration, so a rectangular distribution of errors with a half-width of 0.5 nm was assumed, rather than the 0.14 nm assumed in Reference 2; the effect on the expanded uncertainty is negligible. Table 2 lists all identifiable sources of uncertainty.

The values given in Table 1 include a net systematic error of 0.009 µm. That is, those values are equal to the values calculated from Equation (1) plus the 0.009 µm correction derived from Table 2. A direct calculation from the data on the diskette should, therefore, yield a value 0.009 µm less than the values stated in Table 1, provided that the user has made no corrections for systematic errors.

Instructions for Use: Remove the locking screw from the housing and place the housing in the apparatus. Taking care not to exert a lateral force, push the brass barrel forward until the fiber protrudes fully from the housing. Rotate the brass barrel until the flat facet is parallel to the plane of the scan.

Prepare the opposite end of the fiber and direct light at wavelength 1.31 µm or 1.55 µm into the core. Follow the recommendations of Reference 1. Most specifically, use a mode stripper that consists of one or more turns around a mandrel ~30 mm in diameter. Locate the mandrel at least 30 cm from the radiating end of the fiber and keep the fiber fairly straight thereafter. A cladding mode stripper is not necessary. Take data every 0.5° or less, continue to 26° if possible, and use a detector or pinhole that subtends 0.5° or less as seen from the location of the fiber.

Calculate the mode-field diameter from Equation (1): First, find the center of the pattern and average the left half of the pattern and the right half of the pattern. Then integrate Equation (1) numerically. Equivalently, calculate the mode-field diameter from the left and right halves of the data set and average the two results. An error of the order of 0.010 µm may result if you use a rectangular or trapezoidal rule for integrating. (That error might be more or less than 0.010 µm with a different kind of fiber.) It is preferable, therefore, to use an extended trapezoidal rule, as in Reference 2, or Simpson's rule for integration; NIST used an extended trapezoidal rule [3]. Finally, calculate the systematic errors for your own system, as in Table 2. This procedure yields the mode-field diameter according to the TIA's specification.

NIST recommends that mode-field diameter measurements be carried out as closely as possible to the wavelengths of 1.31 µm or 1.55 µm. If that is not possible, then use a laser whose wavelength λ is within 0.03 µm of the appropriate wavelength λ_0 and correct the resulting mode-field diameter by subtracting the value $b(\lambda - \lambda_0)$; see Table 3.

Performing this operation will incur an additional component of uncertainty

$$u_b \left| \lambda - \lambda_0 \right| \tag{2}$$

where u_b is the standard uncertainty of the slope b and the coverage factor is $k = 1$. This component of uncertainty must be added in quadrature with all other components to determine the combined standard uncertainty [1].

The far-field intensity will display cusps near −12.5° and 12.5° at the wavelength of 1.31 µm and near −14° and 14° at 1.55 µm. These cusps are zero crossings of the electric field and are typically six orders of magnitude below the maximum intensity. Secondary maxima, or sidelobes, should be visible at angles beyond the angles of the cusps. Additional sidelobes may be visible beyond these first sidelobes. The maximum intensity beyond the first sidelobes should not exceed a value six orders of magnitude below the intensity at 0°. If it does, then there may be scattered light in the system. Scattered light will cause a systematic error whose value must be estimated. See Reference 2 for further details.

As the fiber end ages, it may become contaminated and scatter light. Therefore, monitor the intensity beyond the first sidelobes, and use the data as an indication of the quality of the end. If the end seems contaminated, it may be possible to clean it with a piece of adhesive tape such as Scotch™ Magic™ Tape[1]. To do so, form a loop of tape with the sticky side out. Using your finger, touch the end of the fiber lightly once or twice with the loop of tape. The loop provides strain relief and protects the fiber from breaking. (Note: Do not attempt to clean SRM 2520, Optical Fiber Diameter Standard, in this way, inasmuch as the adhesive tape method may damage the periphery of the fiber.)

It may also be possible to clean the end of the fiber with a gentle stream of filtered air or with an ultrasonic cleaner. We recommend only spectroscopic grade ethanol or acetone (not reagent grade) or deionized water such as is used in the semiconductor industry. A mixture of ethanol and deionized water may work well. Take care, however, that the fluid not touch the housing, where it may loosen or dissolve contaminants.

Acceptable agreement between a user's measurements and the certified value is demonstrated if any part of the range defined by the NIST certified value and its expanded uncertainty overlaps any part of the user's tolerance band defined by the measured mean and the user-defined value of acceptable uncertainty. Specifically, if an instrument yields a value of mode-field diameter that is not consistent with the calibrated value (that is, the chosen confidence interval of the measurement does not overlap that of the standard), then find the origin of the discrepancy and eliminate it, or expand the confidence interval accordingly.

Inappropriate Use Warning: Many of the factors that give rise to systematic errors will cause consistent errors from specimen to specimen, even if the specimens represent radically different types of fiber. Others, however, will yield different errors with different fiber types. Therefore, we do not recommend that the SRM be used to effect a correction, but rather suggest that it be used only to verify the calibration of an instrument.

Storage and Handling: This SRM should be stored in the container in which it was received. To store the fiber, simply retract the end into the aluminum housing and replace the socket head screw into the side of the housing. Replace the housing into the recessed shipping container and screw down the plastic top. Store the entire assembly in a clean environment or put it into an airtight plastic bag. Do not expose the housing or the calibrated end to the environment more than is necessary.

Use of the Diskette: Each SRM includes a 3.5 inch floppy disk with four data files in ASCII format. The data files have names such as sn*xx*_131.prn and sn*xx*_155.prn. Here, "sn" stands for "serial number," and "*xx*" is the serial number of your SRM. "131" and "155" stand for the wavelengths 1.31 µm and 1.55 µm. The extender ".prn" indicates that the file contains the raw data. Occasionally, noise may cause some values to be below 0. Therefore, we provide a second data set with the extender ".dat"; these data are limited to values greater than 10^{-9}, so that they may be conveniently plotted on a semi-logarithmic scale. Finally, the data were gathered from −26° to 26° in angular increments of 0.4°.

[1] Certain commercial materials and equipment are identified to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are the best available for the purpose.

Discussion of Effective Area: The effective area of a single-mode fiber is defined differently from πw_0^2, where w_0 is the mode-field *radius* of the fiber [1]. The effective area may be calculated by performing an inverse Hankel transform and applying the formula

$$A_{\mathrm{eff}} = 2\pi [\int I(r)\, r\, \mathrm{d}r]^2 \,/\, \int I^2(r)\, r\, \mathrm{d}r \tag{3}$$

where $I(r)$ is the intensity as a function of radial position r in the plane of the end of the fiber and the integrations are carried out from 0 to ∞.

Since this SRM is intended for calibrating far-field systems, it is certified only for mode-field diameter. It is not certified for effective area. Very roughly, however, if A is the effective area, we may write

$$A \approx \pi w_0^2 \tag{4}$$

whence

$$\Delta A \approx 2\pi w_0 \, \Delta w_0 \tag{5}$$

where ΔA is the standard uncertainty of A, and $\Delta w_0 = 15$ nm is the combined standard uncertainty of the mode-field radius. Thus, if the mode-field radius is 4.5 µm, then $A \approx 65$ µm^2 and $\Delta A \approx 0.4$ µm^2. The expanded uncertainty is approximately 0.8 µm^2.

Table 2. Components of Uncertainty

Source	Method of Analysis	Correction (µm)	Uncertainty (µm)
Numerical integration	Simulation		<0.001
Angle of scan	Data	-0.005	0.003
Angular errors	Simulation + specification		0.006
Finite pinhole	Simulation	0.008	0.002
Repeatability and noise	Data		0.003
Gain nonlinearity	Data + simulation		0.008
Axial position of fiber	Geometry		0.001
Cleave angle	Geometry		<0.001
Vertical position	Data		<0.001
Lateral position	Data		0.001
Scattered light	Data + simulation	0.006	0.003
Noncircularity	Measurements + theory		0.008
Wavelength	Data		0.001
Fresnel coefficients	Simulation + theory		<0.001
Additive correction		0.009	
Combined standard uncertainty	▯		0.015
Expanded uncertainty (coverage factor of 2)	▯		0.030

Table 3. Corrections for Wavelength

Nominal Wavelength (μm)	Slope, b	Slope Uncertainty, u_b
1.31	4.64	0.08
1.55	5.35	0.07

REFERENCES

[1] "Measurement of Mode Field Diameter of Single-Mode Optical Fiber," Fiberoptic Test Procedure FOTP-191, TIA/EIA-455-191, Telecommunications Industry Association (2500 Wilson Boulevard, Arlington, VA 22201), (1998).

[2] Wittmann, R.C. and Young, M., "Are the Formulas for Mode-Field Diameter Correct?" *Tech. Digest*, *Symposium on Optical Fiber Measurements*, *1998*, Natl. Inst. Stand. Technol. Spec. Publ. 930, U.S. Government Printing Office, Washington DC, pp. 69-72, (1998).

[3] Young, M., "Mode-Field Diameter of Single-Mode Optical Fiber by Far-Field Scanning," *Appl. Opt.* **37**, pp. 5605-5619, (1998).

[4] Young, M., "Mode-Field Diameter of Single-Mode Optical Fiber by Far-Field Scanning: Addendum," *Appl. Opt.* **37**, p. 8361, (1998).

[5] "Measurement of the Effective Area of Single-Mode Optical Fiber," Fiberoptic Test Procedure FOTP-132, TIA/EIA-455-132, Telecommunications Industry Association, (1998).

It is the responsibility of users of this SRM to assure that the certificate in their possession is current. This can be accomplished by contacting the SRM Program at: Telephone (301) 975-6776 (select "Certificates"), Fax (301) 926-4751, e-mail srminfo@nist.gov, or via the Internet http://ts.nist.gov/srm.