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Calibration Service for Instruments that Measure Laser Beam Diameter

Shao Yang

NIST National Institute of Standards and Technology
United States Department of Commerce

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[1]At Boulder, CO 80305
[2]Some elements at Boulder, CO

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CONTENTS

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This document describes the calibration service for instruments that measure laser beam diameter. An overview of the measurement procedures, measurement system, and uncertainty analysis is presented. A sample measurement report is included in this document that is similar to what is provided to the customer. The measurement report contains an absolute correction factor and a summary of the uncertainty assessment for the device under test.

Key words: laser beam diameter; laser beam diameter measurement; laser beam profile; slit scan measurement;

1. Introduction

This measurement service compares laser beam diameter measurements made with the NIST beam diameter measurement system with those made by a test meter (or device under test, DUT) (usually a laser beam profiler). The measured beam diameter is the second-order moment (or 4σ) beam diameter defined by the International Organization for Standardization (ISO) [1 – 3]. A test laser beam, generated with a single-mode optical fiber and an optical fiber collimator at a wavelength of 830 nm, is used as a stable source for laser beam diameter measurements. The nominal measured beam diameter is 2.2 mm with a typical expanded (k=2) uncertainty of 0.3 %. The service identification (ID) for the measurement service in this document is 42220C.

2. Calibration Service Summary

The provision of calibration services (or measurement services in this document) is an essential element of the work of the Sources, Detectors, and Displays Group (as part of the Electronics and Electrical Engineering Laboratory). In the conduct of this work, as in all its efforts, the group is committed to excellence that is characteristic of a global leader in measurements and standards. Our goal is to provide measurement services that meet the needs of our customers and, through continuous improvement, to anticipate their needs, exceed their expectations, and deliver outstanding value to the nation.

This calibration service is performed under conditions determined by the system setup and the test beam generated therewith. For these measurements, the customer's meter, or device under test (DUT), is sent to NIST, where it is used to measure the test beam diameter. The test beam diameter has been characterized by the NIST beam diameter measurement setup. The DUT should be able to measure the second-order moment (or

4σ) beam diameter defined by ISO, but may use different measurement methods other than the NIST measurement. At the completion of the calibration measurements, the DUT and a calibration report are sent to the customer. The calibration report summarizes the results of the measurements and provides a list of the associated measurement uncertainties. (See Table 6.1.) The NIST beam diameter measurement system for this calibration service was designed and built at NIST.

More information can be found in NIST Optoelectronics Division Quality Manual (QM-II) for descriptions of NIST, the NIST Optoelectronics Division, and their quality systems.

3. Theory of Measurement

3.1 System Basics and Measurement Principle

This service involves a direct comparison between measurements of the beam diameter of a test laser beam made with the DUT and those of the NIST beam diameter measurement system. The test beam is generated with a semiconductor diode laser, coupled into a single-mode fiber and expanded with a fiber collimator (as shown in Figure 3.1). The laser beam is stable in profile, power, and wavelength. The test beam profile is determined by the fiber-collimator, constant over a wide power range controlled with a fiber attenuator to meet the measurement power requirements for different test meters. Because the beam diameter varies along the propagation axis, the DUT and NIST measurements are made at the same position with reasonable tolerance. The NIST measurement system employs the slit scan method, where a narrow slit with a finite length scans across the beam in two orthogonal directions. The slit length and the scan distance are selected according to conditions stipulated in the ISO standard [1 – 3] for laser beam diameter measurements. The circularity of the test beam is sufficiently good that the identification of the major and minor axes of the test beam is not necessary within our quoted uncertainties.

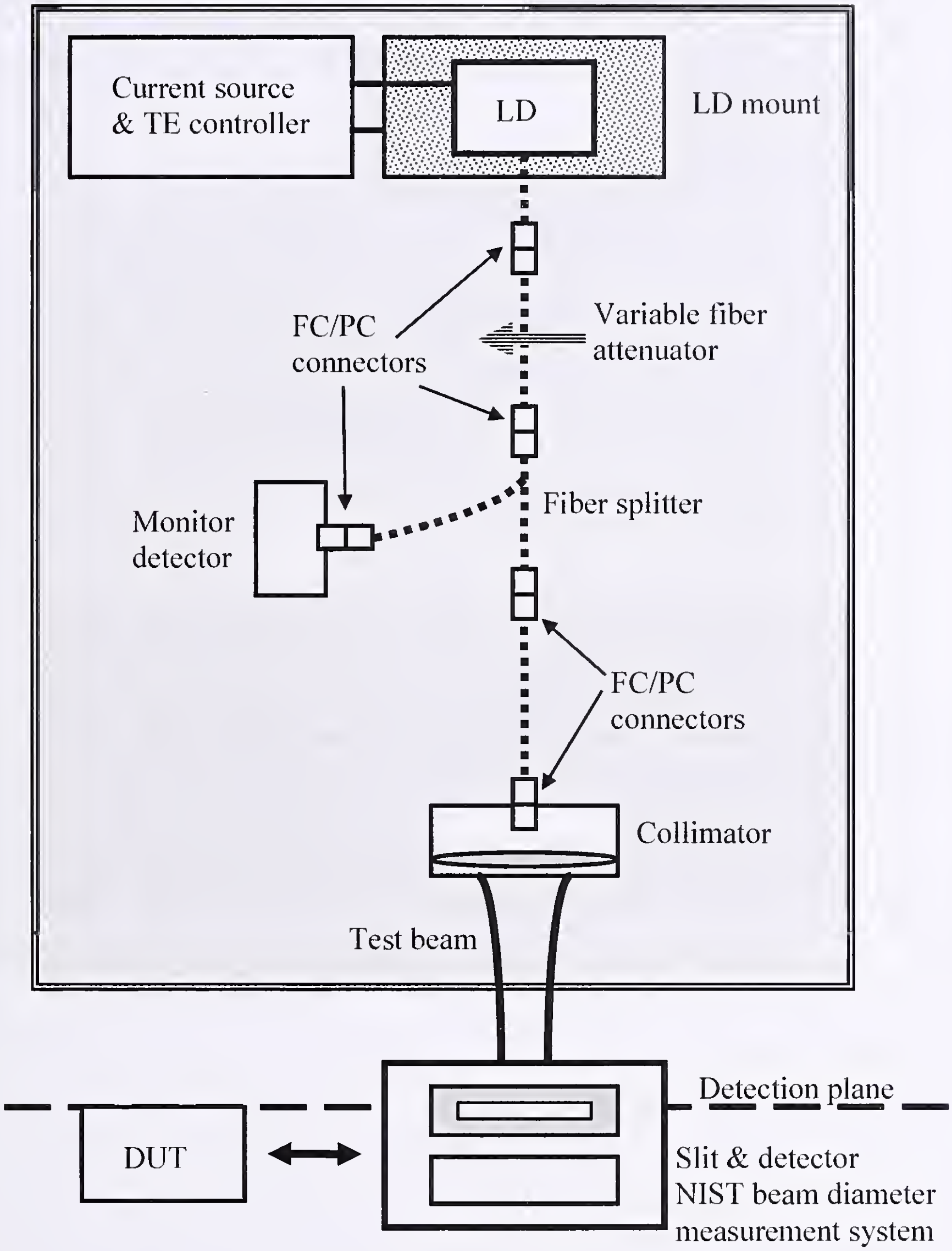

Figure 3.1. Schematic diagram of the NIST beam diameter measurement system. The gray box is the test beam source. The fiber-coupled 830 nm laser diode (LD) is mounted on a temperature-controlled platform. All the fiber components are single-mode at 830 nm and linked with FC/PC connectors. The single-mode fiber (dotted line) and the collimator determine the diameter of the test beam. The slit and detector are placed on a rotation indexing mount and moved together during the scan. The DUT and the slit are in the same measurement plane from the collimator.

3.2 Measurement Equations

ISO defines laser beam diameter by use of the second order moments of the beam power density distribution $I(x, y)$ [1 - 3]:

$$\sigma_x^2 = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x-\bar{x})^2 I(x,y)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)dxdy}, \qquad 3.1$$

and

$$\sigma_y^2 = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(y-\bar{y})^2 I(x,y)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)dxdy}. \qquad 3.2$$

$\bar{x}$ and $\bar{y}$ are the centroid coordinates of the power density distribution:

$$\bar{x} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xI(x,y)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)dxdy}, \qquad 3.3$$

$$\bar{y} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} yI(x,y)dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)dxdy}. \qquad 3.4$$

The generalized beam diameter, used to represent the beam width and also called the 4σ beam diameter, is defined as

$$d = 4\sqrt{\frac{\sigma_x^2 + \sigma_y^2}{2}} \equiv 4\sigma. \qquad 3.5$$

This expression defines the beam diameter uniquely for all laser beam power distributions. For beams with a perfectly Gaussian profile, the 4σ beam diameter is exactly the width between the two $1/e^2$ points of the peak of the profile.

The integrations in Equations 3.1 to 3.4,

$$P(x) = \int_{-\infty}^{\infty} I(x,y)dy, \qquad 3.6$$

and

$$Q(y) = \int_{-\infty}^{\infty} I(x,y)dx, \qquad 3.7$$

are power intensities of the beam along the x and y directions and represent powers in an infinitely long and narrow slit, $P(x)$ and $Q(y)$, at positions x and y, respectively. We may rewrite Equations 3.1 to 3.4 as

$$\sigma_x^2 = \frac{\int_{-\infty}^{\infty}(x-\bar{x})^2 P(x)dx}{\int_{-\infty}^{\infty} P(x)dx}, \qquad 3.8$$

$$\sigma_y^2 = \frac{\int_{-\infty}^{\infty}(y-\bar{y})^2 Q(y)dy}{\int_{-\infty}^{\infty} Q(y)dy}, \qquad 3.9$$

$$\bar{x} = \frac{\int_{-\infty}^{\infty} xP(x)dx}{\int_{-\infty}^{\infty} P(x)dx}, \qquad 3.10$$

$$\bar{y} = \frac{\int_{-\infty}^{\infty} yQ(y)dy}{\int_{-\infty}^{\infty} Q(y)dy}. \qquad 3.11$$

Equations 3.5 through 3.11 are the basis of slit scan measurement of the 4σ laser beam diameter. The integration limits in Equations 3.1 to 3.4 and 3.6 to 3.11 are from negative to positive infinity. This is impossible to realize in practice. Finite integration limits must be used in all practical measurements. The ISO standard stipulates that a square integration area whose width is three times the beam diameter in both the major and minor axes for a general elliptical beam be used for the evaluation of beam diameter. This uniquely defines the beam diameter for almost all practical beam profiles as shown in Figure 3.2 for an ideal Gaussian beam and the test beam in this measurement system. The ideal Gaussian beam has a theoretical beam diameter of 2.19 mm, and the measured test beam diameter is 2.194 mm. (For an ideal Gaussian beam, its measured beam diameter within this area differs from the true diameter by less than 5 millionth of a percent.) It is also impractical in many real measurements to limit the widths of measurement area to exactly three times the beam diameter. A reasonable deviation must be tolerated. Figure 3.3 shows the percentage deviation of the measured beam diameter with different integration areas from that measured with the exact integration area stipulated in ISO standard for the NIST test beam. The integration limits of the NIST slit scan measurement are from 0 mm to 7 mm. This measurement area is within the range of integration area for the 0.1 % uncertainty limit for the test beam, as shown in Figure 3.3. For test beam profilers, the measurement areas are always finite but may be different, depending on the measurement principle and the design of the meter.

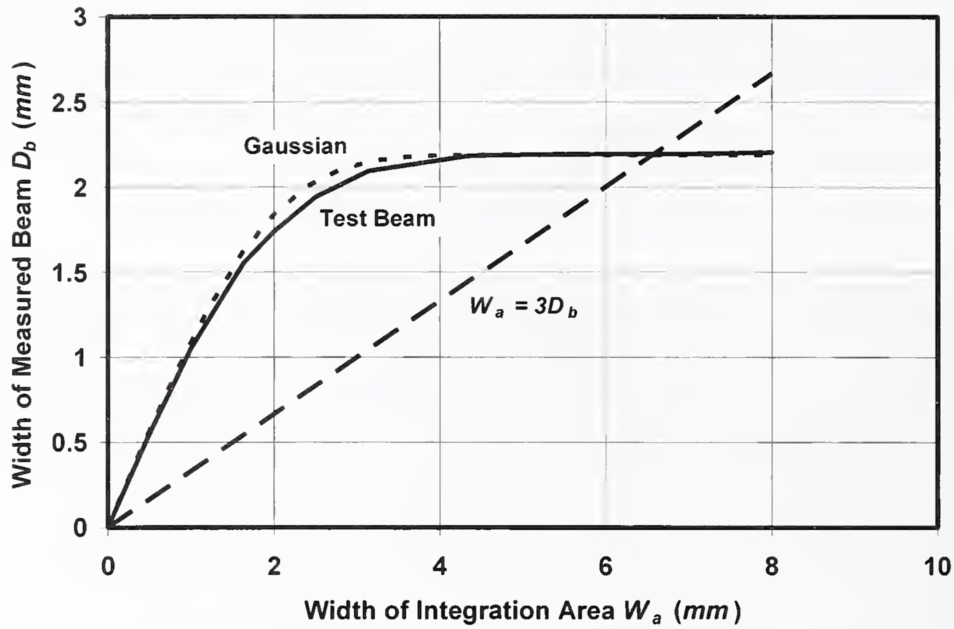

Figure 3.2 An integration area with a width of three times the beam diameter defines measured beam diameter for the test beam and the best fit Gaussian beam. The solid and dotted curves show the measured beam diameter, D_b, of the test beam and the Gaussian beam as a function of the width of the integration area, W_a. The dashed straight line is $W_a=3\times D_b$. The intersecting point defines the beam diameter and the corresponding width of the measurement area. The theoretical beam diameter of the Gaussian beam is 2.19 mm. The measured test beam diameter is 2.194 mm.

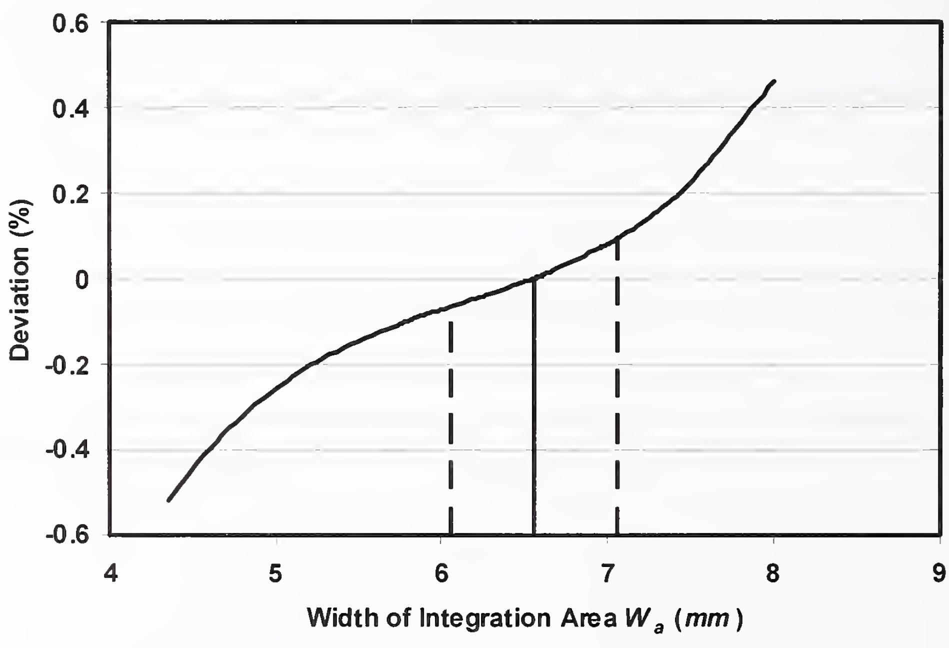

Figure 3.3: Percentage deviation of the test beam diameter measured within an area of width W_a from that measured within the ISO defined area. The solid vertical line indicates the ISO defined measurement area. The two dashed vertical lines define the allowed range of measurement area that keeps the related Type B uncertainty contribution of measured beam diameter below 0.1 %. Due to a small side lope peaked at the position of about 8 mm, the curve does not level off as expected for a more well-behaved beam profile.

3.3 Data Analysis

In the NIST slit scan measurement system, the width of the slit is 10 µm and the length is 7 mm. For one single complete measurement, the slit scans in both the horizontal (x) and vertical (y) directions at steps of 25 µm for a range of 8 mm. Using iterations in the data processing software, the centroid and a 7 mm range around it in each direction are found and used in the calculation. The integration area is a square of 7 mm × 7 mm. The data analysis of the DUT is performed with the software provided by the customer. The final result is displayed in the meter and recorded.

4. Measurement System

The NIST calibration service for instruments that measure laser beam diameter consists of a system to create a stable laser beam with a nominal diameter of 2.2 mm, referred to as the test beam, and a system characterizing the test beam by use of the slit scan method. A schematic of the beam creation-characterization system is shown in Figure 3.1.

4.1 Test Beam

A laser diode operating at a nominal wavelength of 830 nm and driven in constant current mode, and mounted on a temperature controlled platform serves as the source for the test beam. The laser is pigtailed with a single-mode fiber connected to a variable fiber attenuator. The fiber attenuator can be used to adjust the test beam intensity for different measurement conditions. The far end of the attenuator is connected to a 98/2 fiber splitter. The minor leg of the fiber splitter is coupled to a monitor detector, providing the means to correct for power drifts of the laser. The main leg of the fiber splitter is connected to a two-meter long fiber coupled to a beam collimator. The nominal focal length of the collimator is 11 mm.

The test beam exiting the collimator serves as the working beam diameter standard for the measurements. The laser beam has a nearly Gaussian profile with a long tail. The beam has an ellipticity ratio better than 0.995, as based on results of two-dimensional pinhole scan, slit-scan, and camera-based measurements. The beam width should ideally be measured at the beam waist, which is the conjugate point of the fiber end face from the collimator lens (the back focal point) for an ideal Gaussian beam with perfect alignment of the collimator. However, the actual test beam waist is at a distance much longer than this theoretical position, due to the non-ideal Gaussian beam and imperfect alignment of the collimator. A series of beam width measurements shows that at convenient working distances between 50 mm and 100 mm from the collimator, the beam width changes by approximately 1 µm for a path length change of 5 mm, corresponding to a full converging angle of 0.01°, allowing for a large positioning tolerance with very low uncertainty. The beam width varies slightly as a function of the laser wavelength [4, 5]. We have observed that the laser wavelength varies by as much as 0.11 nm or 0.011 % during a four-hour period (typical duration of an entire beam width calibration), which leads to a change in beam width of 0.24 µm. The beam width also varies slightly as a function of the temperature of the fiber [4, 5]. For example, a change of 2 °C in temperature results in a change of 0.002 % in the fiber mode field diameter, or a change of 0.05 μm in the test beam width.

4.2 Scanning Slit Measurement System

For the characterization of the test beam diameter, the NIST measurement system uses the scanning slit method. The width of the slit is 10 μm (±1 μm) and the length is 7 mm (±25 μm). The long axis of the slit is perpendicular to the scan axis. For one complete measurement, the slit is scanned in both the horizontal (x) and vertical (y) directions at incremental steps of 25 μm, for a full range of 8 mm. The resolution of the scanning linear stages is 0.05 μm. The slit is mounted on an indexed rotation stage in order to change the orientation of the slit for the horizontal and vertical scan measurements.

4.3 Data Acquisition

The data acquisition of DUT measurements follows the instructions of the DUT. For each data point of the NIST slit scan measurement, the slit integrated beam power intensity is acquired simultaneously with a reading of the monitor detector. The scan data are corrected for the laser power drift by applying a normalization factor using the monitor readings and recorded in the scan data file.

5. Standard Operating Procedures

5.1 System Startup

All electronics and other support systems are powered up at least one hour prior to the start of the measurement. All test equipment is allowed to equilibrate with room temperature. The laser is powered at the pre-selected drive current for at least one hour before the measurement in order to allow for the output power to stabilize.

5.2 Optical Alignment

The DUT measurement plane and the NIST scanning slit are aligned in positions at the same distance from the collimator surface within a tolerance of 5 mm. The beam pointing direction is aligned perpendicular to the measurement surface within a tolerance of 2.5°, which is determined from the shift of the centroid of the scanned data at two different distances of the scan position from the collimator. For NIST measurement, the beam is centered within the system scan range with enough scan distance on each side from the center. For DUT measurement, the beam is aligned according to the instructions of the DUT.

5.3 Data Acquisition

Data acquisition consists of several alternations of NIST measurement runs and DUT measurement runs. The number and order of alternations depends on measurement specifics of the DUT. Each measurement run may also consist of several measurements. Each NIST measurement includes one scan in each of the x and y directions. The scan takes 25 μm in each step and covers a range of 8 mm. Each scan datum is acquired simultaneously with a monitor detector reading, which is used to correct the slow drift of the test beam power. Before the first NIST measurement, in the middle of the entire measurement, and after the last NIST measurement, the system baseline is scanned with the beam blocked. All the scans are performed with the collimator-scanning-detector covered in a black box to shield off the stray light from the environment.

Other measurement conditions recorded include test beam wavelength, environment temperature, distance of measurement plane from the collimator, DUT model, serial number, and NIST ID number.

5.4 Data Analysis

For the NIST measurement, the average of the system baseline is obtained first from the baseline measurement data. For each scan in each direction (x or y), a software algorithm determines the centroid, a 7 mm integration area around the centroid, and the second-order moment from the corrected scan data with baseline subtraction. The beam diameter is obtained for every two consecutive scan results in the two, x and y, directions for each NIST measurement. The average of all the measured beam diameters is the NIST measurement result.

The DUT measurement result is obtained according to the instrument instructions. The average of all the DUT measurements is the DUT measurement result.

The ratio of DUT measurement result to the NIST measurement result is the correction factor supplied to the customer.

6. Uncertainty Evaluation

The uncertainty estimates for the NIST laser beam diameter measurements are assessed following guidelines given in NIST Technical Note 1297 [6]. To establish the uncertainty limits, the error sources are separated into Type B errors, whose magnitudes are determined by subjective judgment or other non-statistical methods, and Type A errors, whose magnitudes are obtained statistically from a series of measurements.

All Type B error components are assumed independent and to have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\delta_i$, and zero probability of being outside that region). If the distribution is rectangular, the standard deviation, σ_s, for each Type B error component is equal to $\delta_i/3^{1/2}$ and the total *standard uncertainty* is $(\Sigma\sigma_s^2)^{1/2}$, where the summation is performed over all Type B error components.

Type A errors are assumed to be independent and normally distributed and, consequently, the standard deviation, S_r, for each component is

$$S_r = \sqrt{\frac{\Sigma x^2 - \frac{(\Sigma x)^2}{N}}{N-1}} , \qquad 6.1$$

where the x values represent the individual measurements and N is the number of x values used for a particular Type A error component. The standard deviation of the mean is $S_r/N^{1/2}$, and the total *standard uncertainty* of the mean is $[\Sigma(S_r^2/N)]^{1/2}$, where the summation is carried out for all the Type A error components.

The *expanded uncertainty* is determined by combining the Type A and Type B standard uncertainties in quadrature (the *combined uncertainty*) and multiplying this result by an expansion factor of 2. The expanded uncertainty, U, is then

$$U = 2\sqrt{\Sigma\sigma_s^2 + \Sigma\frac{S_r^2}{N}} . \qquad 6.2$$

The number of decimal places used in reporting the mean value of the calibration factor listed in the calibration report is determined by expressing the expanded uncertainty to two significant digits.

Sources of uncertainties are identified and their contributions to the beam width measurement result are determined by test, or theoretical calculation, or computer simulation, or a combination of these methods. Generalized beam diameter, d, defined in Equation 3.5 is a function of the second order moment diameters $4\sigma_x$ and $4\sigma_y$ measured independently in the slit scan method. The uncertainty contributions $u(\sigma_x)$ and $u(\sigma_y)$ of σ_x and σ_y to the uncertainty $u(d)$ of d follow the law of propagation of uncertainty. Some uncertainty sources, especially the Type A uncertainties, affect σ_x and σ_y independently, and the uncertainties $u(\sigma_x)$ and $u(\sigma_y)$ are uncorrelated. Because the test beam has very good circularity, and these uncertainty sources affect the measurements equally in the two measurement directions, we have $4\sigma_x \approx 4\sigma_y = 4\sigma = d$ and $u(4\sigma_x) \approx u(4\sigma_y) = u(4\sigma)$, and therefore $u(d) = \frac{u(4\sigma)}{\sqrt{2}}$. Some Type B uncertainty sources directly impact the measured beam diameter d, so their influences on $u(4\sigma_x)$ and $u(4\sigma_y)$ are completely correlated, resulting in $u(d) = u(4\sigma)$. Some other Type B sources also have a direct impact on beam width d, but their effect on $u(4\sigma_x)$ and $u(4\sigma_y)$ are neither completely correlated nor completely uncorrelated. Because it is difficult to estimate the degree of correlation, we use the worst-case estimate in their evaluations, that is, assuming they are completely correlated. In the following description of the major uncertainty sources, the values of uncertainties are all their final contributions to the uncertainty of $u(d)$.

6.1 Test Beam Uncertainties

6.1.1 Laser Power Stability (Type A)

Laser power output exhibited fast fluctuations and slow drift. The combined standard deviation of laser power in four hours was 1 %. The standard deviation of the measured laser power was reduced to 0.1 % by applying a power drift correction using input from the monitor detector. Simulation results indicated that this resulted in an uncertainty of 0.1 μm in the beam width measurement.

6.1.2 Interference Pattern (Type A)

Because of the narrow spectral width of the laser beam, interference due to reflections between the fiber end face and the collimator lens resulted in fluctuations in the scanned beam profile. From the raw data, it was estimated that this effect caused a RMS fluctuation of about 0.5 % in the measured signal, resulting in a standard uncertainty of 0.4 μm in the final result, according to simulations.

6.1.3 Wavelength Stability (Type B)

The single-mode fiber beam width is dependent on the laser beam wavelength. Measurements showed that the laser beam wavelength exhibited fast fluctuation and slow drift. Fast fluctuation will cause noise-like effects on the measurement. However, the magnitude of wavelength fast fluctuation is less than 0.003 %, which caused a similar change in beam width magnitude that can be ignored. The slow drift of the wavelength will cause a difference between results of NIST and DUT measurements and a difference between NIST measurements before and after the test meter measurements due to the time difference of the measurements. Test results showed that wavelength drift could be as high as 0.01 % when the laser is operated in constant current mode, which converts to an estimated standard uncertainty in beam width measurement of 0.07 μm, or 0.003 %, which can be ignored.

6.2 Measurement System Uncertainties

6.2.1 Detection Noise (Type A)

Detection noise is the combined result of detector noise (dark current noise, shot noise, etc.) and the readout electronics noise. The detection signal to noise ratio was 5×10^5, resulting in a standard uncertainty of 0.2 μm in the beam width.

6.2.2 Measurement Area (Type B)

The uncertainty limit of the measured beam width due to the difference between the actual measurement area and the ISO defined area is 0.1 %, as described earlier. The standard uncertainty is then 0.06 %.

6.2.3 Optical Axis Tilt (Type B)

Results of multiple realignments and measurements showed that the tilt angle between the optical axis of the beam and the beam profile plane can be controlled within 2.5°. The standard uncertainty of the measured beam width due to this tilt is 0.05 %.

6.2.4 Positioning of the Measurement Plane (Type B)

For a maximum possible difference of 5 mm in the relative longitudinal positions of slit-scan and DUT measurements, a standard uncertainty of 0.6 μm, or 0.03 %, is incurred in the measured beam width.

6.2.5 Detector Nonlinearity (Type B)

Nonlinearity measurement of the NIST detector showed a positive response nonlinearity of up to 2 % occurred at the lower end of the measurement range. Simulations indicated that this results in a standard uncertainty of 0.4 μm or 0.02 % in the beam width.

6.2.6 Slit Tilt (Type B)

The tilt of the slit can be kept within 1° relative to the scan axis. Simulation indicated that this results in a standard uncertainty of 0.4 μm or 0.02 %.

6.2.7 Off-Centroid Slit Scan (Type B)

The scanning slit should ideally be centered at the centroid in the direction orthogonal to the scanning direction. Because the slit cannot be perfectly positioned at the center of the rotation stage, the slit may not be centered at the centroid during the scans. Test results showed that a maximum position error of 200 μm off-center may occur, which may result in a standard uncertainty of 0.6 μm or 0.03 % uncertainty in the measured beam diameter.

Type A uncertainties discussed in 6.1.1, 6.1.2, and 6.2.1 cannot be separately estimated in each and every particular measurement. However, their combined effect contributes to the measurement standard deviation of the NIST and DUT measurements, which are listed in the test report. Other sources of uncertainty we have considered include the finite slit width, scan resolution, effect of ellipticity, and motion accuracy. Their contributions to the overall uncertainty of the beam width measurement are all less than 0.1 μm and deemed negligible. Major uncertainty contributions are listed in Table 6.1.

Source	Uncertainty	
Type A	Standard Deviation (%)	N
NIST measurement	0.02	6
DUT measurement	0.06	30
Type B	Standard Uncertainty (%)	
Measurement area	0.06	
Optical axis (z direction) tilt	0.05	
Relative positioning of detection plane	0.03	
Detector linearity	0.02	
Slit tilt	0.02	
Slit off-centroid	0.03	
Combined standard uncertainty u_c	0.09	
Expanded uncertainty (k=2) $U=k\ u_c$	0.19	

Table 6.1 Example summary of measurement uncertainties associated with NIST and DUT measurements.

7. Quality Control

The measurement services of the Optoelectronic Division make use of quality assurance practices to ensure the validity of measurement results and their uncertainties. Such practices include:

- Repeated measurements/calibrations compared over many time intervals
- Comparison of previous results obtained using multiple measurement methods, if available.
- Routine, periodic measurements with different methods.

For this service, we periodically measure the test beam diameter using three different methods, slit scan, two-dimensional pin-hole scan, and camera-based beam profiling. Figure 7.2 shows the history of the test beam measurements during the period from June 2008 to April 2009.

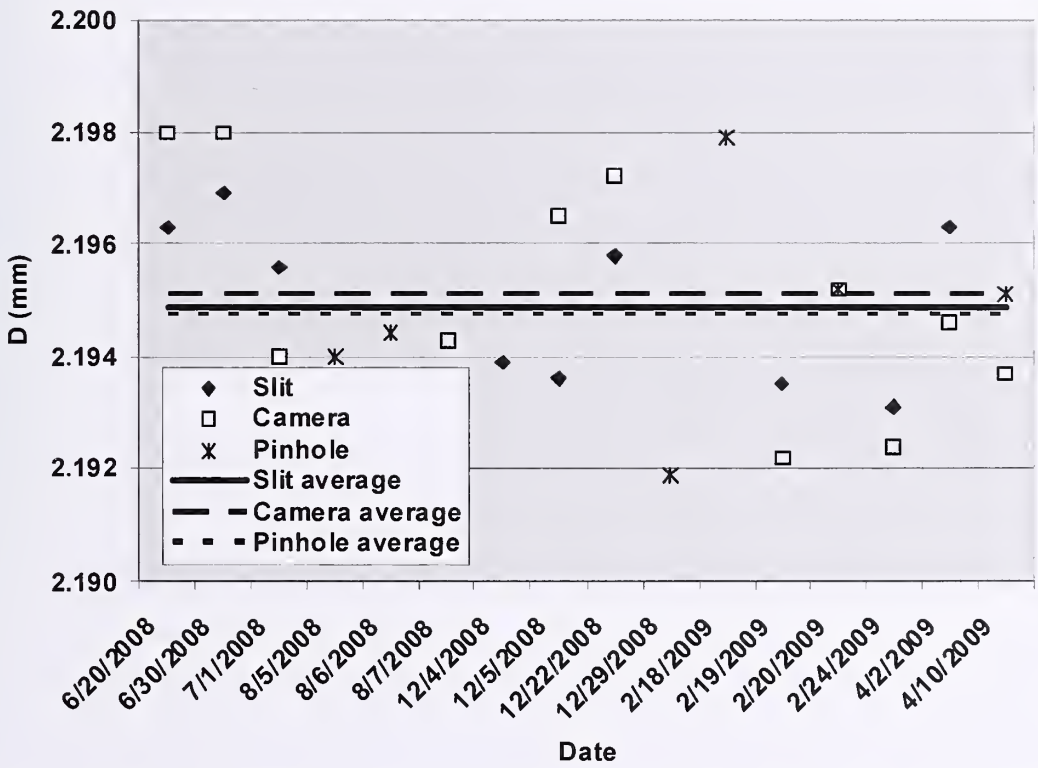

Figure 7.1. Test beam measurements using three different methods, slit scan, two-dimensional pinhole scan, and camera-based beam profiling from June 2008 to April 2009. The average and standard deviation of these measurements are 2.1949 ± 0.0015 mm for slit scan, 2.1951 ± 0.0021 mm for camera beam profiling, and 2.1948 ± 0.0020 mm for pinhole scan.

In the Optoelectronics Division, all calibration, MAP, and remote measurement (RM) services maintain check standards and control charts for periodic test of the measurement service. When available, historic data from previous measurements of the test beam shall be placed into the test folder by the Measurement Services Coordinator after the preparation of the calibration report. The Calibration Leader and the Group Leader shall review this data before signing the calibration reports. If a significant variance from previous results is observed, the Group Leader may require another measurement of the calibration item as a test of measurement system conformance.

8. Summary

NIST provides a calibration service for instruments that measure laser beam diameters. In this document, we have summarized the basic measurement equations, the measurement procedure, and described the quantities that contribute to the relative standard uncertainty.

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Journal of Research of the National Institute of Standards and Technology–Reports NIST research and development in metrology and related fields of physical science, engineering, applied mathematics, statistics, biotechnology, and information technology. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Institute's technical and scientific programs. Issued six times a year.

Nonperiodicals

Monographs–Major contributions to the technical literature on various subjects related to the Institute's scientific and technical activities.

Handbooks–Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications–Include proceedings of conferences sponsored by NIST, NIST annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

National Standard Reference Data Series–Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NIST under the authority of the National Standard Data Act (Public Law 90-396). NOTE: The Journal of Physical and Chemical Reference Data (JPCRD) is published bimonthly for NIST by the American Institute of Physics (AIP). Subscription orders and renewals are available from AIP, P.O. Box 503284, St. Louis, MO 63150-3284.

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