U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ELECTRONICS & ELECTRICAL ENGINEERING LABORATORY
Boulder, Colorado 80303

Report of Special Test

Spatial Uniformity of Laser and Optical Fiber Power Meters and Detectors Used with Lasers (42165S)

LASER POWER METER
Labsphere Model: 3P-LPM-040-SL, S/N 05076191
with Keithley Current Amplifier Model: 428, S/N 1154940

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Measurement Summary

The laser power meter's spatial uniformity was measured using the system shown schematically in Figure 1. The free-space laser beam with approximately Gaussian intensity profile was scanned across the face of the detector. The detector's responsivity was measured relative to that in the detector's

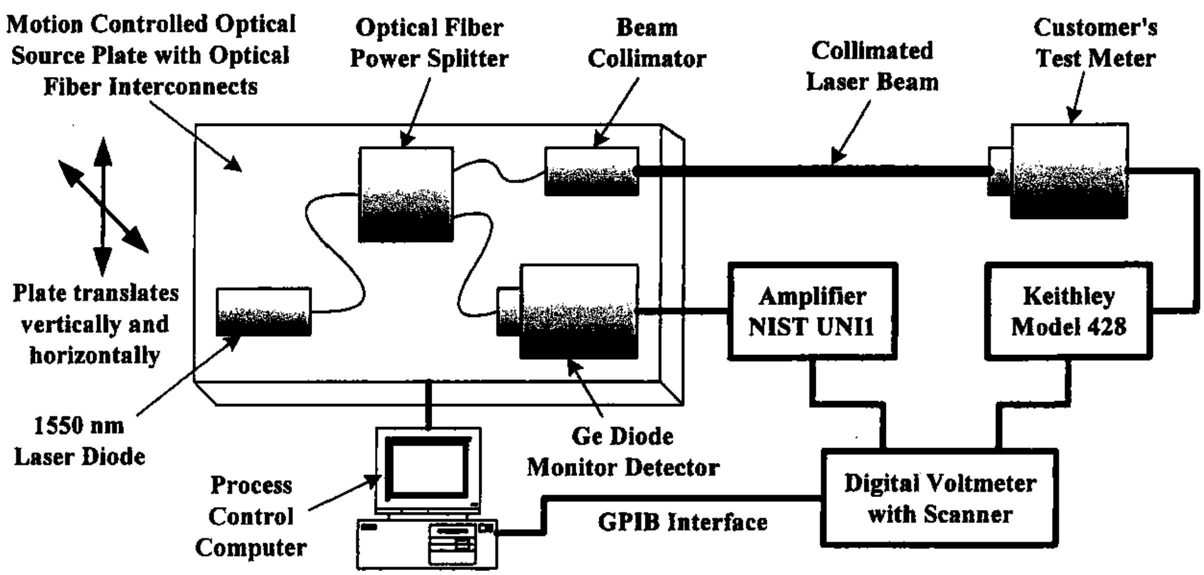

Figure 1. Spatial uniformity measurement system.

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center, and expressed as a percentage of the responsivity in the center. The relative responsivity was sampled at the vertices of a rectangular grid centered in the detector's entrance aperture. A statistical summary of the results is presented in Table I, and graphical representations are shown in Figure 2 and Figure 4.

The detector was mounted on a vertical post using the threaded mounting hole in its base. The axes in the figures are such that the x-axis is horizontal, the y-axis is vertical, and left-right is as if looking at the detector through its entrance aperture.

Table I. Statistical Analysis

Radius from Center (mm)	Relative Responsivity					
	N	Mean (%)	Standard Deviation (%)	Maximum (%)	Minimum (%)	Expanded Uncertainty (k = 3) (%)*
0.5	5	99.99	0.02	100.02	99.96	0.09
1.0	13	100.01	0.05	100.09	99.93	0.09
1.5	29	100.01	0.06	100.11	99.92	0.12
2.0	49	100.01	0.06	100.12	99.87	0.12
2.5	81	100.00	0.07	100.12	99.84	0.12
3.0	113	100.00	0.06	100.14	99.84	0.12
3.5	149	100.00	0.06	100.14	99.84	0.12
4.0	197	100.00	0.06	100.14	99.84	0.12
4.5	253	100.00	0.06	100.19	99.79	0.12
5.0	317	100.00	0.06	100.19	99.79	0.12
5.5	377	100.00	0.06	100.19	99.73	0.12
6.0	441	100.01	0.07	100.20	99.73	0.12
6.5	529	100.01	0.06	100.20	99.73	0.12
7.0	613	100.01	0.06	100.20	99.73	0.12
7.5	709	100.01	0.06	100.20	99.73	0.11
8.0	797	100.02	0.06	100.20	99.73	0.11
8.5	901	100.02	0.07	100.26	99.73	0.12
9.0	1009	100.02	0.07	100.26	99.73	0.12
9.5	1129	100.02	0.07	100.26	99.73	0.12
10.0	1257	100.02	0.07	100.26	99.73	0.12
10.5	1373	100.02	0.07	100.26	99.73	0.12
11.0	1517	100.02	0.07	100.26	99.73	0.12
11.5	1653	100.02	0.07	100.26	99.73	0.12
12.0	1793	100.01	0.12	100.26	97.11	0.12
12.5	1961	99.18	5.07	100.26	35.55	0.13
13.0	2121	94.87	17.68	100.26	2.65	0.15

* - Uncertainty is dominated by a Type A Analysis with $N = 4$, so a coverage factor of $k = 3$ is required for a level of confidence of approximately 95 %.

A statistical analysis of the scanned data is provided in Table I. Statistics are generated for the samples that fall within a circular area centered in the rectangular array. Circular areas with various radiuses are considered, and the number of samples, mean, standard deviation, maximum, minimum, and expanded uncertainty are given in the table.

Each sample was spaced 0.5 mm apart, and the entire detector was scanned 4 times. The average of the 4 scans is shown in Figures 2 and 4, and the standard deviation of the mean was used to calculate the combined standard uncertainty shown in Figure 3. The uncertainty increases when the beam is near the edge of the detector's limiting aperture because of specular and spatial noise. The expanded uncertainty given in Table I is the average combined standard uncertainty for the samples within the area considered, multiplied by the coverage factor.

The laser beam used in the scan had multiple longitudinal modes consisting of approximately 14 spectral lines with vacuum wavelengths from 1547 to 1567 nm. The weighted center wavelength was approximately 1557.6 nm, and the total power in the beam was approximately 0.59 mW. The beam was an approximately Gaussian beam with $1/e^2$ intensity diameter of approximately 2 mm at the integrating sphere's entrance aperture. The detector is in the far-field of the

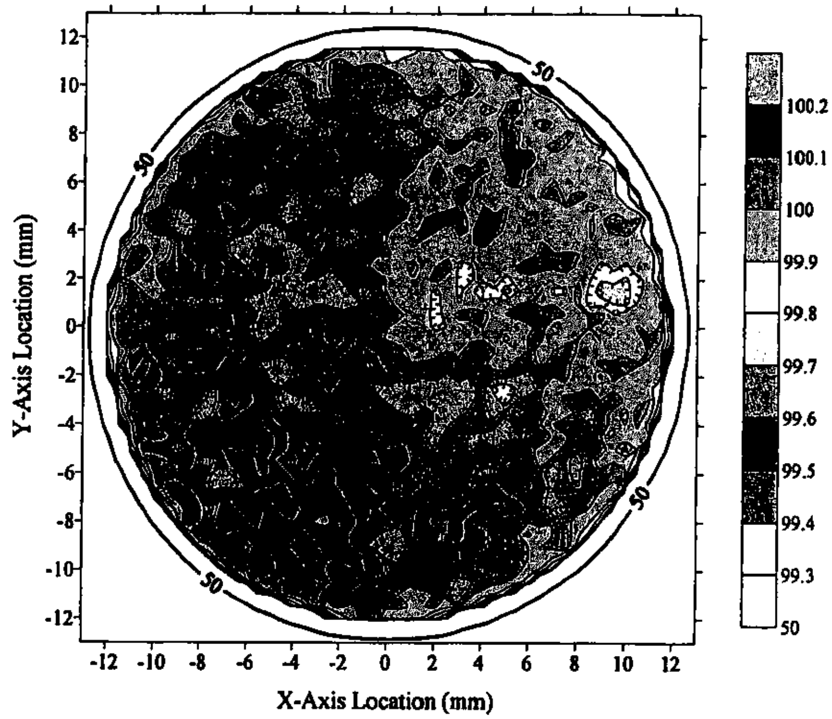

Figure 2. Relative Responsivity (%).

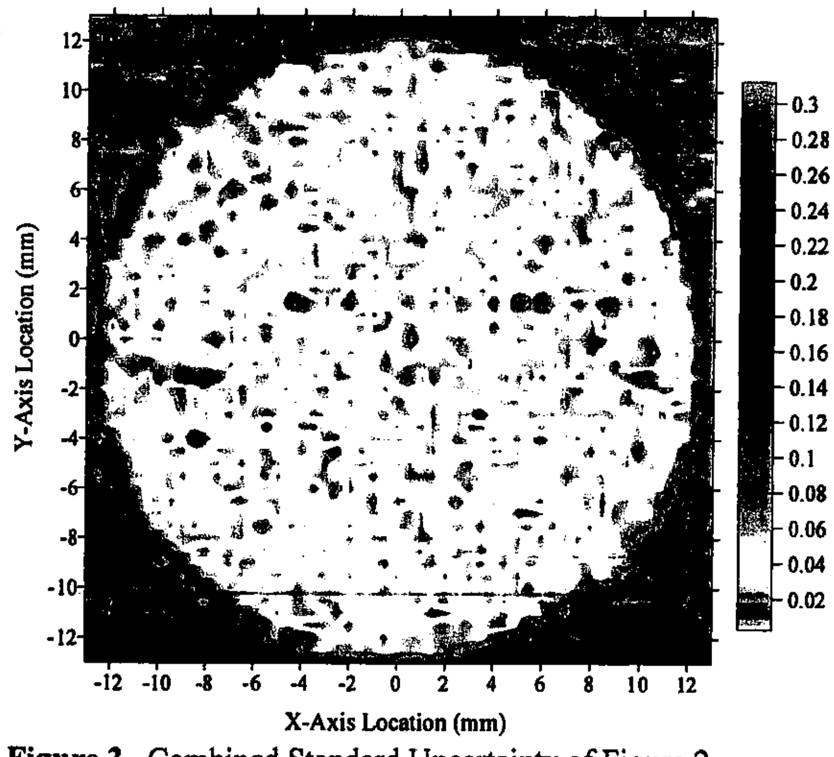

Figure 3. Combined Standard Uncertainty of Figure 2.

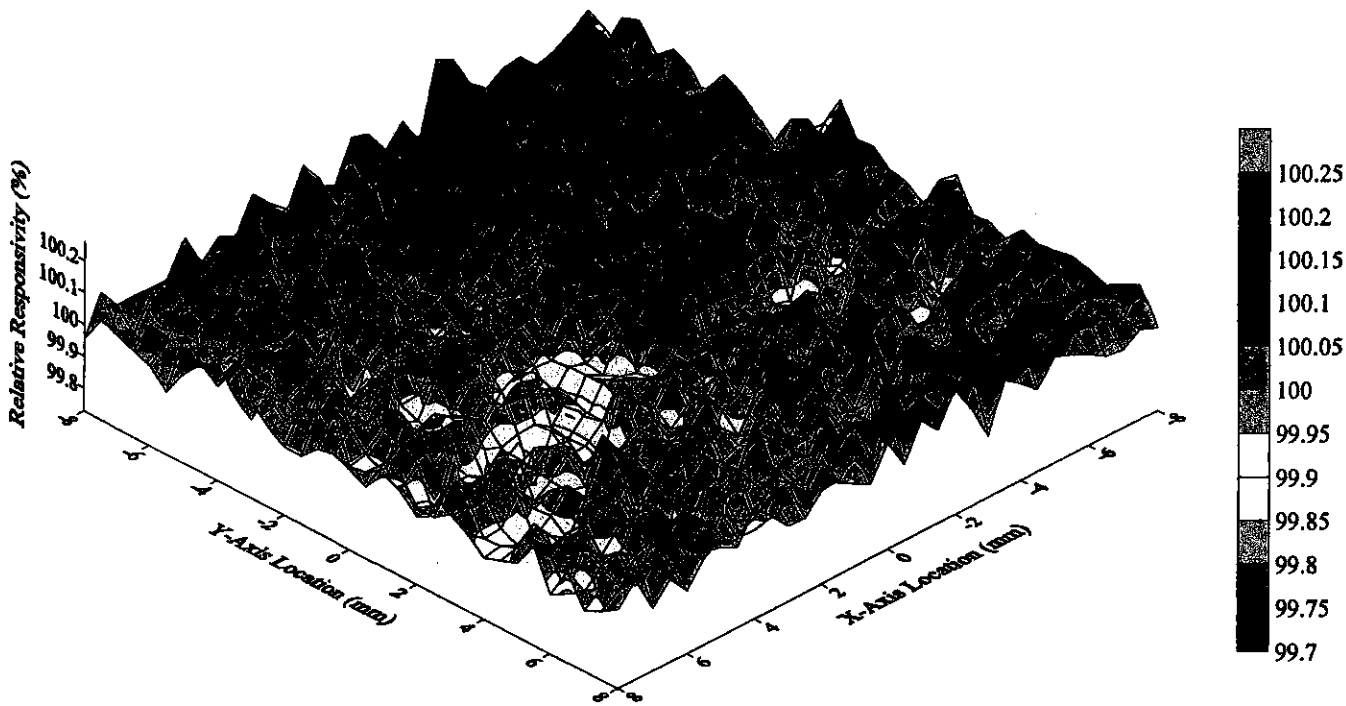

Figure 4. Wireframe map of the relative responsivity around the detector's center.

beam where the full-width beam divergence was approximately 5.6 mRads. The center of the scanning grid was aligned to the center of the entrance aperture by interpolating between the 50 % responsivity points along the x and y axes. The angle of incidence of the beam was within 3 mrad from normal relative to the integrating sphere's entrance aperture.

The test detector's output was amplified using the customer's current amplifier, and the output voltage of the amplifier was measured using the system voltmeter. The NIST precision voltmeter measured the output of the amplifier using 1.7 s integration. The customer's temperature controller was used with the detector, with the diode temperature set to -10 °C. The room temperature was 23 ± 1 °C.

Uncertainty Assessment

Uncertainty estimates for the values given in the NIST calibration report are assessed using the *NIST Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results* (Technical Note 1297). Uncertainty estimates for the values given in the NIST calibration report are assessed using the following technique, which is derived from the official NIST guidelines. Each component of uncertainty that contributes to the uncertainty of the measurement result is represented by an estimated standard deviation, termed the standard uncertainty u. The combined standard uncertainty u_c, which represents the estimated standard deviation of the result, is obtained by combining the individual standard uncertainties. The standard uncertainties are estimated from Type A evaluations, where magnitudes are obtained statistically from a series of measurements; and from Type B evaluations, whose magnitudes are based on scientific judgement using all the relevant information available.

The Type A uncertainty components are assumed to be independent; and consequently, the standard deviation, S_r, for each component is

$$S_r = \sqrt{\frac{\sum_i x_i^2 - \frac{1}{N}\left(\sum_i x_i\right)^2}{N-1}},$$

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

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

The combined standard uncertainty is determined by combining the Type A and Type B standard uncertainties in quadrature; the expanded uncertainty is obtained by multiplying this result by a coverage factor k for a level of confidence of approximately 95 %. For processes with sufficiently large equivalent degrees of freedom, $k = 2$. The expanded uncertainty U is then

$$U = k\sqrt{\sum_s \sigma_S^2 + \sum_r \frac{S_r^2}{N}}.$$

Here the main sources of uncertainty are the uncertainty of the relative voltage measurement, converter linearity, and the measurement repeatability - the standard deviation of the mean of the multiple measurements at each sample point. In the area of interest, the combined sum of the relative voltage measurement and converter linearity is less than 10 ppm, and the standard deviation of the mean is typically much larger. Therefore the standard deviation of the mean dominates, the other terms can be ignored, and the combined standard uncertainty is given by the standard deviation of the mean, shown in Figure 3.

In Table I, the uncertainty of the relative responsivity for the samples in the given area is needed, so the average of the combined standard uncertainties for the samples in the given area is used. Since the standard deviation of the 4 measurements dominates the uncertainty, there are essentially 3 effective degrees of freedom, so a coverage factor of $k = 3$ is needed for determination of the expanded uncertainty with a level of confidence of approximately 95 %.

The number of decimal places used in reporting the values in Table I were determined by expressing the NIST expanded uncertainty to two significant figures. And the tolerances given in the text are expanded uncertainties, with a coverage factor of $k = 2$.

For the Director,
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