Real-Time Scanning Goniometric Radiometer for Rapid Characterization of Laser Diodes and VCSELs

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Abstract

For highly divergent laser sources such as edge-emitting laser diodes (LD's) or vertical cavity surface emitting lasers (VCSELs), the most appropriate measures of beam quality are obtained from the angular spatial irradiance distribution I(θ,ϕ). This is because the highly divergent nature of the beam and the finite dimensions of detectors and camera sensors makes it extremely difficult if not impossible to measure them, from both physical and cost perspectives. As such, measurements of the angular profile have traditionally been performed using instrumentation systems commonly known as "goniometers" or more properly, goniometric radiometers. These systems comprise a detector and a fixture for holding the source, and the measurement is made either by moving the detector about the source at a fixed radius, or by rotating the source with the detector stationary. Measurements made using these conventional goniometers are often very time consuming, with single scans taking anywhere from several seconds in the fastest systems up to 1 hour for the more typical slow systems. We describe an improvement to existing methods, called the "scanning goniometric radiometer". This technique offers up to 3 or more orders of magnitude increase in measurement speed, up to 2 orders of magnitude improvement in angular sampling resolution, and a measurement field-of-view up to 360°. With the scanning goniometric radiometer, the source and detector are stationary, and a rotating optical collector, in the form of an optical fiber or fiber optic bundle or a light pipe, rotates about the source and delivers light to the detector. This arrangement allows for real-time scans of the angular profile through a single azimuth of the source, with single scan profiles obtained in times of the order of 10 to 100 milliseconds. The smooth rotational motion of the optical collector allows angular spatial sampling resolution of the order of 0.001° to be easily achieved. In one measurement configuration the source must be rotated to obtain a full hemispherical or "3D" measure of the far-field pattern. An alternative configuration uses a moveable turning mirror between the source and the optical collector, which allows for a full 3D far-field measurement with the source stationary. The trade-off here is a reduced field-of-view determined by the extent of the turning mirror and the source displacement. The primary advantage of the scanning goniometric radiometer technique over the conventional methods is speed of measurement. One benefit of the speed is that considerations such as source instability due to temperature or current fluctuations can be ignored during the time of the measurement. The speed also allows for real-time observation of such characteristics as kinks or spatial mode-hopping. It also allows for greater numbers of devices to be measured economically and for statistical analysis of the performance of individual devices. Finally, these systems can measure the profiles without attenuation, and at much higher spatial sampling resolution than can be obtained using lenses and camera sensors such as CCD's.

Keywords: Laser Diodes, VCSELs, Far-field Profile, Goniometric Radiometer, ISO 11146, LED, Optical Fibers, Optical Waveguides, Mode-Field Diameter

1. Introduction

For highly divergent laser sources such as edge-emitting laser diodes (LD’s) or vertical cavity surface emitting lasers (VCSELs), the most appropriate measures of beam quality are obtained from the angular spatial irradiance distribution I(θ,ϕ). Methods called for in the ISO/DIS 11146 standard to measure the planar spatial distribution I(x,y) are typically inappropriate for such large divergence sources. In many cases the beam divergence exceeds the 0.8 radian (45.8°) paraxial limit imposed by the standard, or the test lens requirements for beams with divergence near the limit are not simple; e.g. beam truncation considerations. Often times the tails of the angular distribution are of interest. For edge-emitting laser diodes, the beam profile can extend out to angles exceeding 2.5 radians at the 0.1% amplitude level. For VCSELs, the tails can extend to angles greater than 1 radian at the 0.1% amplitude level. For these reasons, and due to the finite dimensions of detectors and camera sensors, measurement of the planar distribution is extremely difficult if not impossible to perform, depending on the level of accuracy required. Measurement of the angular distribution overcomes all these issues.

Measurements of the angular profile have traditionally been performed using instrumentation systems commonly known as “goniometers” or more properly, goniometric radiometers. These systems, illustrated in figure 1, comprise a detector and a fixture for holding the source, and the measurement is made either by moving the detector about the source at a fixed radius, (Figure 1a) or by rotating the source with the detector stationary, (Figure 1b).

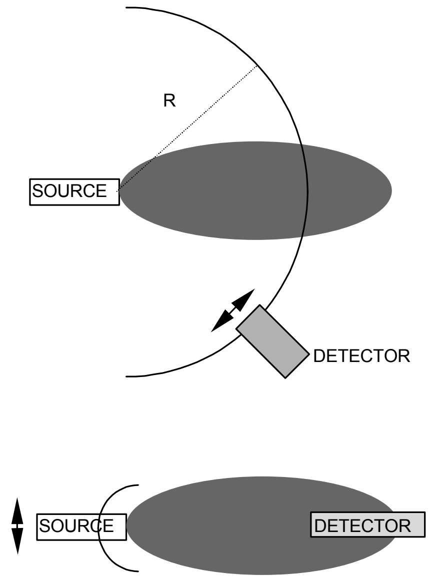


Figure 1. Conventional goniometric techniques: a.) Detector scanned at fixed radius R about source, and b.) Source rotated in front of detector at radius R.

2. Scanning Goniometric Radiometer Techniques

An improvement to these methods is the scanning goniometric technique. Here, the source and detector are stationary, and a rotating optical collector, in the form of an optical fiber or fiber optic bundle or a light pipe, rotates about the source and delivers light to the detector. This arrangement allows for real-time scans of the angular profile through a single azimuth of the source.

The technique is illustrated in Figure 2a showing a source positioned at the center of rotation of the optical collector. Each rotation of the optical collector generates a profile with full 180°(actually 360°) field-of-view and real-time performance is obtained by rotating the collector at a rate on the order of 10 – 100 Hz. Then the time for a single scan is of the order of 10 - 100 ms. In this configuration, a full 3-dimensional measure of the angular distribution can be obtained by rotating the source about its axis so that profiles through different azimuths are measured.

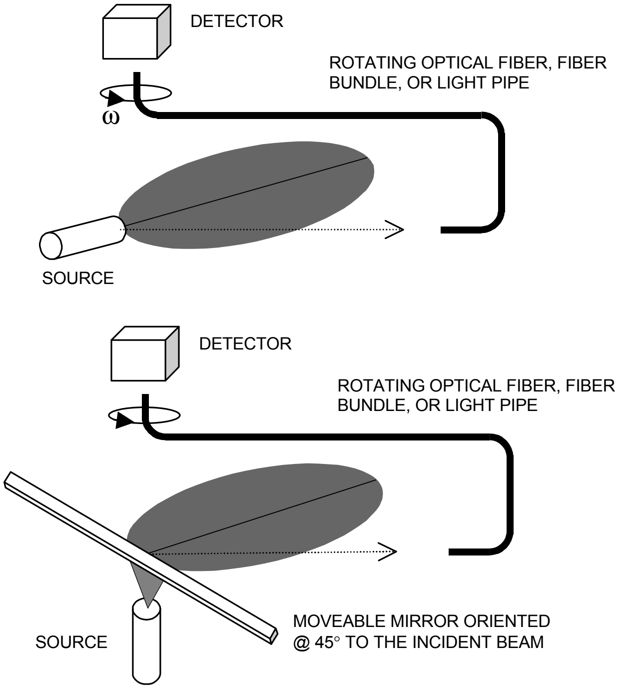


Figure 2. Scanning Goniometric Techniques: a.) Source at center of scan, and b.) Turning mirror at center of scan with source below.

A variation of this technique uses a mirror at the center of rotation oriented at 45° to the scan plane with the source pointing at the mirror, shown in figure 2b. The mirror turns the beam into the scan plane. Each position of the mirror provides measurement of different azimuth angles of the source, so by rotating the mirror through 180° a full 3-dimensional measure of the profile is obtained. Because the scan is eccentric in this case, mathematical corrections for scan geometry and eccentricity, and collector obliquity must be performed.

When the turning mirror is used, the field-of-view is reduced. The length of the mirror and the displacement of the source to the mirror determine the reduction. However, for typical compact geometries with mirror length of 10 cm and source displacement of 1 cm, fields-of-view on the order of ±80° are easily achieved. For the same mirror length but with displacement distances on the order of 5 cm, the field-of-view is reduced to approximately ±30°. These larger displacements provide easy access to sources. For example, for wafer level testing of VCSELs the space allows for probe access, viewing for alignment, and device marking.

The angular sampling is extremely accurate because of the smooth mechanical motion of rotation of the optical collector, and the use of an optical position encoder. Spatial sampling resolution of the order of 0.001° is easily achieved.

The linearity of the single detector/amplifier assures accurate irradiance measurement over up to 8 decades of optical power. With this wide dynamic range, source powers from sub-microwatts to 10's of Watts can be conveniently measured, without the need for attenuation. Also, it allows the tails of the distribution to be measured with high accuracy, down to amplitude levels less than 0.01% of the peak.

2.1 Mathematical Corrections for the Turning Mirror Configuration

2.1.1 Scan Eccentricity and Angular Transformation

The scan path is eccentric because the source is displaced from the center of rotation of the turning mirror, which is also the scan path center. If the displacement distance is "d", then the virtual source is displaced "d" from the center of the scan. This geometry is shown in Figure 3. Data is acquired from the sensor at radius R from the mirror, and over a range of angles $q¢$, where $-90° \le q¢ \le +90°$. However, the distance to the source, $r(q)$, is greater than $R+d$ except at $q = q¢ = 0°$, and the angle with respect to the source, q, is less than $q¢$ except at $q¢ = 0°$, where they are equal. To obtain the radiation pattern of the source, it is therefore necessary to correct the amplitude of the data to correct for the scan eccentricity, and also to transform the angle from the scan space to the space of the source.

The distance between the source and the detector as a function of angle, $r(q')$,is given by the expression:

$$r(q') = \sqrt{R^2 + d^2 + 2Rd\cos q'}$$

The measured data will manifest this distance variation as an error, so that an isotropic radiation distribution would show an angular dependence, which, instead of being constant, is proportional to the inverse square of $r(q')$. However, this error can be entirely compensated by applying a geometric correction factor $r^2(q')/(R+d)^2$, which normalizes the data to the far-field measured at 0°.

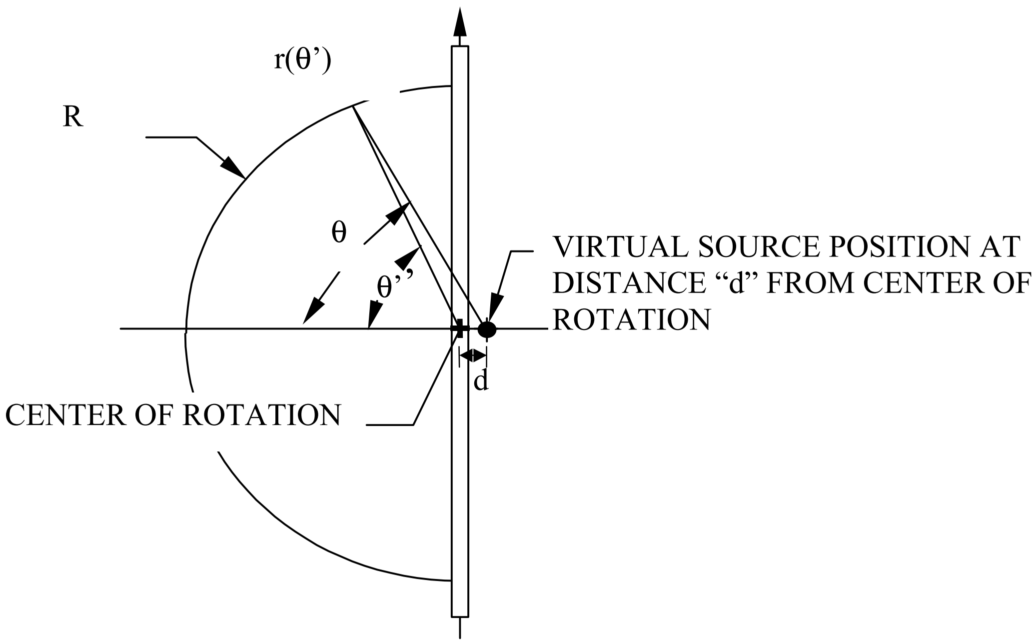


Figure 3. Scan Geometry of the Scanning Goniometric Radiometer.

The angular transformation is derived from the geometry shown in Figure 4. The transformation is given by the following expression:

$$q = \cos^{-1}\left[\frac{d + R\cos q'}{\sqrt{R^2 + d^2 + 2Rd\cos q'}}\right]$$

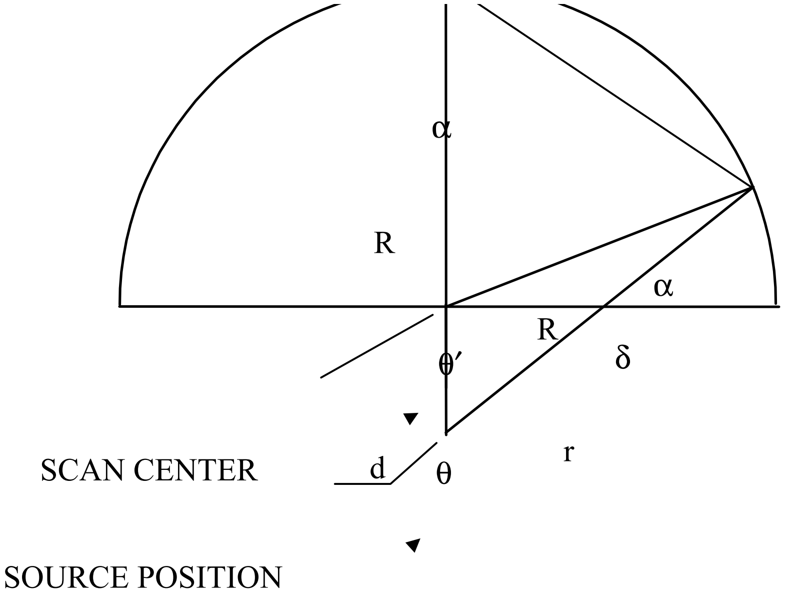


Figure 4. Geometry for determining the angular transformation to convert angles in scan space to angles in source space.

2.1.2 Obliquity Factor Correction for Optical Collector Orientation

In general, the normal to the surface of the optical collector does not point at the source, but instead points at the scan center. This is evident from the discussion of the angular transformation above. A correction must be made to account for this change in orientation of the optical collector with respect to the source, which occurs as the scan angle changes. The change in angle is the difference between the scan angle θ’ and the source angle θ. The obliquity correction factor, F(θ’), is the cosine of the angular difference:

$$F(q') = \frac{1}{\cos(q - q')}$$

2.1.3 Angular Field-of View

The angular scan range is equal to the angle subtended by the source at the turning mirror. From the geometry shown in Figure 3, the angular scan range, q_{range}, is given by the expression:

$$q_{range} = \pm\left\{90 - \tan^{-1}\frac{2d}{l}\right\}$$

where d = displacement from the turning mirror center, and

l = length of turning mirror.

As examples, for l = 10 cm and d = 0.2 cm, $q_{range} \cong \pm 87.7°$, and for l = 10 cm and d = 0.5 cm, $q_{range} \cong \pm 84.3°$.

For very large values of d, an additional limitation to the field-of-view arises due to the numerical aperture of the fibers in the fiber bundle.

2.1.4 Polarization Effects

The s and p polarization components of the source will in general propagate differently through the optical system. These polarization effects will be present due to:

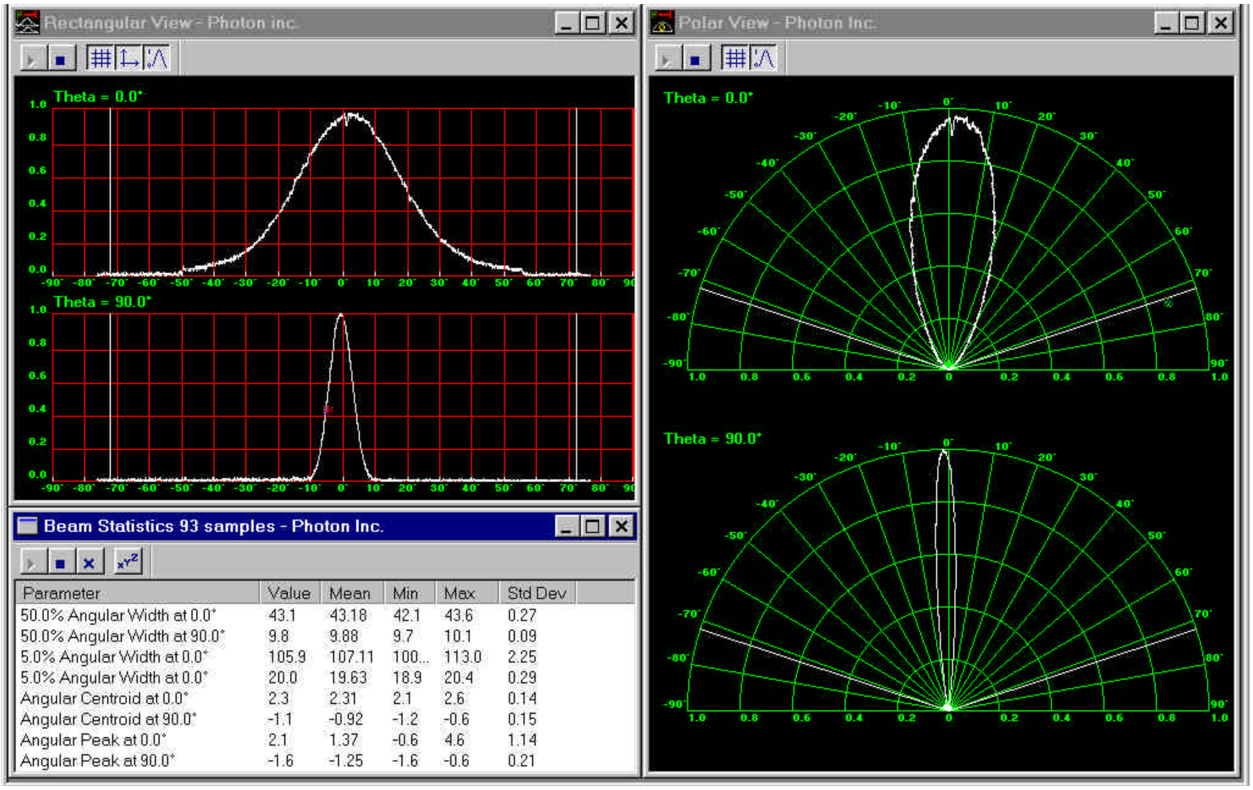
1. polarization dependent reflection from the turning mirror;
2. polarization dependent transmission in the optical fiber bundle.

For the turning mirror, the magnitude of the effect is a function of the angle of incidence of the light on the reflecting surfaces, and the material properties of the reflecting surface. Polarization effects in the optical fiber depend on the fiber type.

Polarization effects will be greatest at the turning mirror, where the angle of incidence of source light will range from essentially 0° - 90°. The use of silver for the mirror surface material significantly reduces this effect to the order of a few percent or less. The polarization effects in the fiber bundle are also minimal. If necessary, both can be compensated by calibration.

3. Example Profile Data

Typical far-field profiles measured along the “fast” and “slow” axes of an edge-emitting laser diode using the scanning goniometric radiometer are displayed in figure 5. Also shown is a table of angular widths, centroid position (device pointing), and peak locations determined from the profile data, with statistics for 93 dual scans. In this case the dual scan update rate is approximately 0.5 Hz. The single scan update rate is 5 Hz. Characteristics such as device pointing can be observed in real time. The data was acquired and digitized with 8-bit resolution.



Parameter	Value	Mean	Min	Max	Std Dev
50.0% Angular Width at 0.0°	43.1	43.18	42.1	43.6	0.27
50.0% Angular Width at 90.0°	9.8	9.88	9.7	10.1	0.09
5.0% Angular Width at 0.0°	105.9	107.11	100...	113.0	2.25
5.0% Angular Width at 0.0°	20.0	19.63	18.9	20.4	0.29
Angular Centroid at 0.0°	2.3	2.31	2.1	2.6	0.14
Angular Centroid at 90.0°	-1.1	-0.92	-1.2	-0.6	0.15
Angular Peak at 0.0°	2.1	1.37	-0.6	4.6	1.14
Angular Peak at 90.0°	-1.6	-1.25	-1.6	-0.6	0.21

Figure 5. Orthogonal scan data for the fast and slow axes of an edge-emitting laser diode, shown in rectangular and polar coordinates. Device pointing is easily observed.

Angular profiles for the same device acquired and digitized with 16-bit resolution are shown in Figure 6. Here the wide angular extent of the tails of the distribution at low amplitude is observed. In addition, truncation of the profiles due to the device package at ~±52° can be seen.

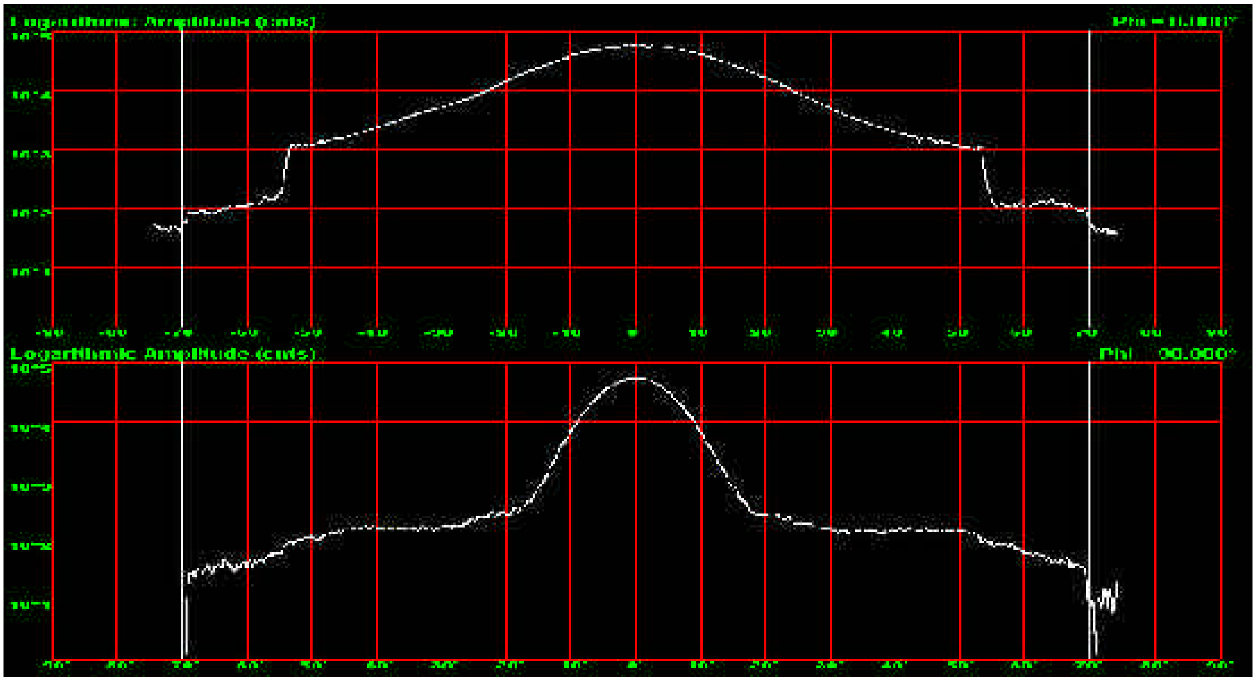


Figure 6. Orthogonal scan data for the fast and slow axes of the edge-emitting laser diode of figure 5, shown in rectangular coordinates on a logarithmic scale. These profiles show the wide angular extent of the tails of the irradiance distribution at low amplitude levels. Also, truncation due to the package at ~±52° can be seen in both profiles.

The power of the technique is illustrated in figures 7 and 8, which show topographic views of the full 3-dimensional profile for 2 different packaged laser diodes. Each view comprises 200 scans at incremental azimuth angles of 0.9 degrees through each source. In figure 7, higher order mode structure is clearly visible at the center of the profile. In figure 8, in addition to the overall far-field pattern, diffraction rings generated by dust on the device package can be seen. Both sets of data were acquired in approximately 90 seconds. Using the old conventional goniometric techniques, which typically required about 30 minutes to obtain a single scan, each data set represents approximately 100 hours of measurement time.

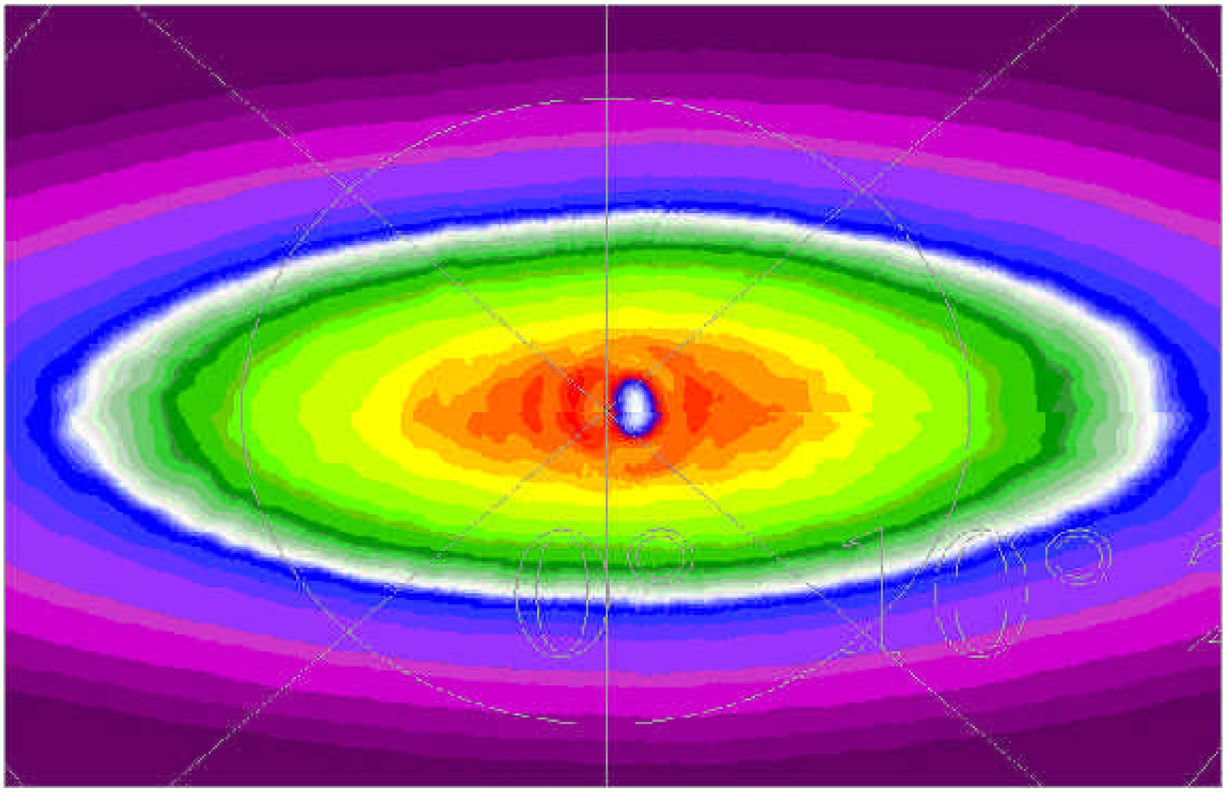


Figure 7. Complete far-field profile of a packaged laser diode, generated from 200 azimuthal scans at 0.9-degree increments using the scanning goniometric radiometer technique. Higher order mode structure can be seen at the center of the pattern

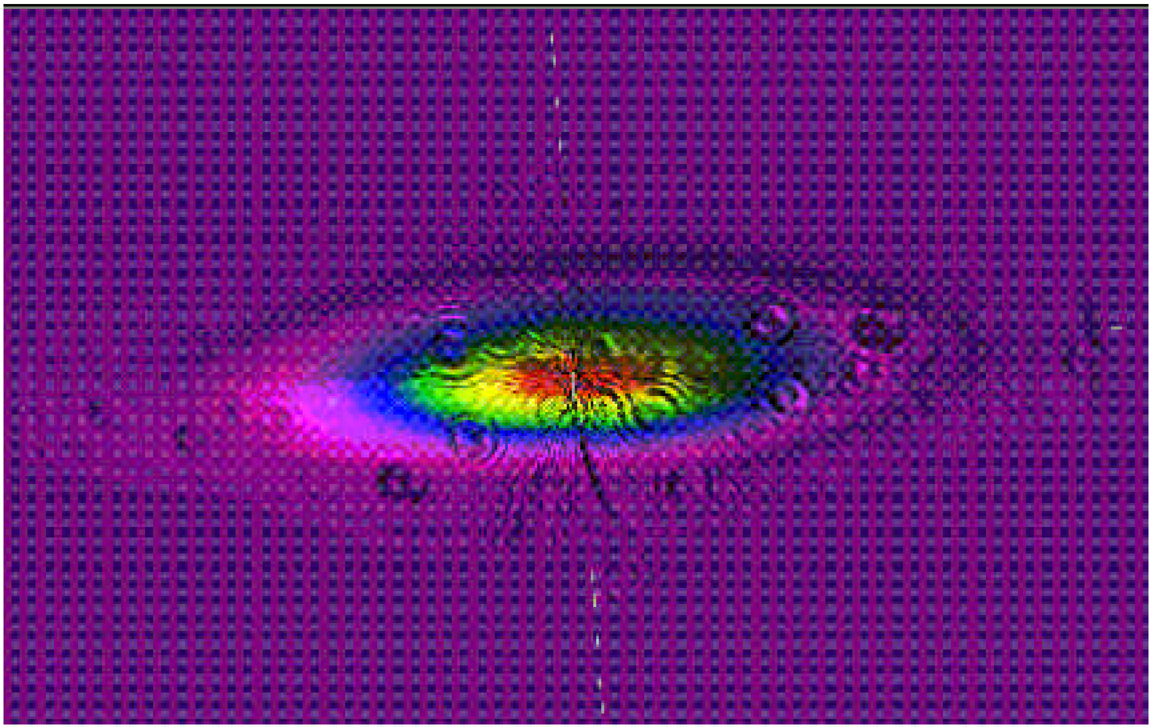


Figure 8. Complete far-field profile of a packaged laser diode, generated from 200 azimuthal scans at 0.9-degree increments using the scanning goniometric radiometer technique. Diffraction rings due to dust on the package window are clearly seen.

4. Conclusions

The scanning goniometric radiometer technique provides a rapid and accurate method for measuring the far-field angular irradiance distribution of highly divergent optical sources, such as edge-emitting laser diodes, VCSELs, and LED's, optical fibers and waveguides as well. The advantages of the technique are many. It provides high speed of measurement, allowing for real-time observation of far-field profiles, and laser effects such as spatial mode-hopping or the onset of kinks. Also, because of the speed of measurement, considerations such as source instability due to temperature or current fluctuations can be ignored. It has the ability to measure up to a full 360° field-of-view. It offers high spatial sampling resolution and accuracy; much higher than can be obtained using lenses and camera sensors such as CCD's. It has wide dynamic range, allowing for measurement of the irradiance distribution of sources covering a wide range of powers without attenuation, from sub-microwatts to 10's of Watts. The wide dynamic range also allows for observation down to less than the 0.01% level in the tails. Finally, the speed of measurement and the high accuracy allow for the testing of greater numbers of devices both economically and reliably.

5. References

International Standard ISO/DIS 11146 "Lasers and laser related equipment - Test methods for laser beam parameters – Beam widths, divergence angle and beam propagation factor", International Organization for Standardization, 1999.

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