The Scanning Goniometric Radiometer: 
A Revolutionary Technique for Characterizing Divergent Light Sources: Laser Diodes, VCSELs, Optical Fibers, Waveguides, LEDs,...

Presented by:
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Who is Photon Inc.?

Photon Inc. is a San Jose, CA manufacturer of instruments that measure the spatial properties of light from virtually any light source—lasers, laser diodes, light-emitting diodes, optical fiber, waveguides, and VCSELs. Since its founding in 1984, Photon has been committed to offering unique solutions to difficult challenges and providing superior after-sales service and support. Abiding by this mission has resulted in robust products that meet the needs of satisfied customers worldwide.
Photon instrument profile...

- Laser diodes and VCSELs
- Optical components
- Collimators based on laser diodes, VCSELs, and fibers
- Optical assemblies
- Lensed, tapered and/or single-mode fibers
- Medical lasers and systems
- Solid state lasers and systems
- Industrial lasers and systems
- Gas lasers
- Laser scanners and systems
- Optical memory
Photon instruments measure these parameters

- Spot size and profile
- Beam position
- Multiple beam analysis
- Collimation or divergence
- Gaussian fit
- $M^2$
- Near-field profiles
- Far-field profiles
- Mode field diameter
- Effective area
- Numerical aperture
Scanning Goniometric Radiometer

ABSTRACT

Measurements of the irradiance pattern of light sources has traditionally been performed using instrumentation systems commonly referred to as “goniometers” or “goniophotometers”. 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 on a rotation stage with the detector stationary. With these systems, the time required to measure the far field pattern along a single azimuth ranges typically from a few minutes up to an hour. These time constraints made it difficult if not practically impossible to perform more complete characterization of the irradiance pattern of optical sources. An improvement to these methods, the “scanning goniometric radiometer”, 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°. Details of the new technique, and application examples for measurements of laser diodes, VCSELs, LEDs and optical fiber will be presented.
Irradiance Measurement of Divergent Light Sources

New Scanning Goniometric Radiometer Technique

Measurement Examples: LDs, VCSELs, Fiber, LEDs

Near-Field Characterization from Far-Field Measurement

Summary
Why Perform Measurements?

- Research & Development
  - Verify Designs
  - Data for Modeling
- Manufacturing
  - Qualify Devices (prior to value-added packaging)
  - Device Life Testing
  - Product Quality Assurance
Scanning Goniometric Radiometer

Applications - Divergent Light Sources

- Semiconductor Lasers
  - Edge-emitting Laser Diodes (LDs)
  - Vertical Cavity Surface Emitting Lasers (VCSELs)
- Light Emitting Diodes (LEDs)
- Optical Fibers
  - Single-mode Fiber
  - Multi-mode Fiber
  - Specialty Fibers
- Optical Waveguides
- Semiconductor Optical Amplifiers
- Photonic Bandgap Structures
- Diffuse Scatterers
  - e.g., Laptop Computer Diffuser Screens
- Novel Sources....
Scanning Goniometric Radiometer
Application: Laser Diodes

- Measure:
  - Angular width of Fast and Slow axes
  - Beam Pointing
  - Kink Onset
  - Spatial Mode Structure
- Verify Component Specifications
- Qualify devices before adding Value
Scanning Goniometric Radiometer

Application: Fiber Optics

- Single-Mode Fiber
- Multi-Mode Fiber
- Specialty Fiber
  - TEC
  - Erbium Doped
  - DCF
  - Others...
- Lensed Fiber
- Fiber Bundles
Scanning Goniometric Radiometer

Application: Scatterometry

- Bi-directional Scatter Distribution Function (BSDF)
  - Reflectance (BRDF)
  - Transmittance (BTDF)
  - Volume (BVDF)

- Total Integrated Scatter (TIS)
Scanning Goniometric Radiometer

Application: Illumination

- Measure Illuminance of Luminaires
  - Lamps
  - Lighting Fixtures
  - Headlights
  - Traffic Signals
  - etc...
Goniometric Radiometer

Conventional Goniometric Measurement

Stationary Source/ Moving Detector

Moving Source/ Stationary Detector

Scan Time Typically Slow: seconds to hour range
New Goniometric Scanning Method: Stationary Source/Stationary Detector

- Real-Time Single Azimuth Scans
- Provides 3D Measure on Hemisphere
**Goniometric Radiometer**

New Goniometric Scanning Method

**Stationary Source/ Stationary Detector**

Source at center of scan

Fold Mirror at center of scan with source below
Goniometric Radiometer

Principle of Operation
Angular Transformation

Converts angles in Scan space to angles in Source space.

\[ \theta = \cos^{-1}\left[ \frac{d + R \cos \theta'}{\sqrt{R^2 + d^2 + 2Rd \cos \theta'}} \right] \]
Obliquity Factor Correction

The Collection fiber bundle points at Scan Center.

Obliquity Factor = $1/cos(\theta - \theta') = 1/cos (\delta)$
Scan Eccentricity Correction

\[ r(\theta') = \sqrt{R^2 + d^2 + 2Rd \cos \theta'} \]
Angular Field-of-View

Instrument Field-of View is determined by:

- Length “L” of the Fold Mirror
- Distance “d” between source and fold mirror
- NA of Collection Fiber Bundle can also be a factor when d ~ R_{scan}

Example: For L = 10 cm and d = 1.5 cm: FOV = ± 73.3°

- Width of the Fold Mirror determines allowable Source Dimension
Goniometric Radiometer

Scan Geometry

OPTICAL AXIS

DETECTOR
(0.69° nominal FOV)

SCAN DIRECTION
0.05° sampling

θ = 0°

θ = -90°

θ = 90°

ϕ = 90°

ϕ = 0°

0.9° azimuth angle increments

SOURCE

FRONT OF INSTRUMENT
Scanning Goniometric Radiometer
Possible to Scan at Arbitrary Radii
Goniometric Radiometer

LD 8900, LD 8900R
Goniometric Radiometer

LD 8900, LD 8900R
**LD 8900/LD 8900R**

**Data Acquisition**

- 0.055° or Finer Sample Resolution
- 3241 Data Points/Scan
- Scan Radius: 84 mm
- Maximum Field of View: ± 72°
- Single or Perpendicular Scan Modes
  - Arbitrary Azimuth Angle
- 3D Scan Mode
  - 10, 20, 50, 100, or 200 Azimuthal Scans
- CW or Pulsed Sources
Goniometric Radiometer

Ease of Use

- Use Like a Power Meter
- Center the Source in the Aperture
- Set the Gain
- Acquire Profile Data/Parameters
- Simple GUI
- Simple Custom Interfacing
**Goniometric Radiometer**

**Device Interface**

- Simple Mechanical Device Mounts
  - Positions the Source in the Aperture
- Alignment Pins
  - Mechanical Reference to Optical Axis
WARNING!
The following contains graphical depictions of actual optical device irradiance profiles. Viewer Discretion Advised!
LD 8900 Goniometric Radiometer

LD Measurements
LD 8900 Goniometric Radiometer
Edge-emitting Laser Diode
Orthogonal Scans: Rectangular View
LD 8900 Goniometric Radiometer
Edge-emitting Laser Diode
Orthogonal Scans: Polar View
LD 8900 Goniometric Radiometer
Packaged LD: Topographic View
LD 8900 Goniometric Radiometer
Packaged LD: 3D Rectangular View
LD 8900 Goniometric Radiometer
Packaged LD: 3D Polar View
LD 8900 Goniometric Radiometer
Packaged LD: 3D View
LD 8900 Goniometric Radiometer
Packaged LD with Dust on Window
LD 8900 Goniometric Radiometer
Packaged LD with Fingerprint on Window
LD 8900 Goniometric Radiometer

LED Measurements
LD 8900 Goniometric Radiometer

3D Polar Logarithmic Profile of an LED
LD 8900 Goniometric Radiometer
LED Measurements
LD 8900 Goniometric Radiometer
3D Rectangular Profile of an LED
LD 8900 Goniometric Radiometer
Topographic Profile of an LED
LD 8900 Goniometric Radiometer

3D Profile of an LED
LD 8900 Goniometric Radiometer

Power View: LED Data

- Power in cones around optical axis (mW)
  - Total Power (mW): 1.000
  - Power within cone:
    - 5.0°: 0.020
    - 10.0°: 0.077
    - 45.0°: 0.787
  - Cone with % power:
    - 25.00%: 18.484°
    - 50.00%: 27.092°
    - 75.00%: 38.525°
  - 3D Centroid:
    - Theta: -1.46°
    - Phi: 20.37°
### Goniometric Radiometer

**Beam Statistics View with Pass/ Fail Limit Analysis**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Std Dev</th>
<th>Min Limit</th>
<th>Max Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0% Angular Width at 0.0° (deg)</td>
<td>133.8</td>
<td>133.88</td>
<td>133.7</td>
<td>134.1</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0% Angular Width at 90.0° (deg)</td>
<td>133.2</td>
<td>133.28</td>
<td>133.0</td>
<td>133.6</td>
<td>0.17</td>
<td></td>
<td></td>
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<tr>
<td>13.5% Angular Width at 0.0° (deg)</td>
<td>129.4</td>
<td>129.36</td>
<td>129.2</td>
<td>129.5</td>
<td>0.06</td>
<td>126.0</td>
<td>130.0</td>
</tr>
<tr>
<td>13.5% Angular Width at 90.0° (deg)</td>
<td>128.7</td>
<td>128.78</td>
<td>128.5</td>
<td>129.0</td>
<td>0.14</td>
<td>125.0</td>
<td>130.0</td>
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<tr>
<td>60.0% Angular Width at 0.0° (deg)</td>
<td>64.9</td>
<td>64.91</td>
<td>64.7</td>
<td>65.2</td>
<td>0.08</td>
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<tr>
<td>60.0% Angular Width at 90.0° (deg)</td>
<td>63.9</td>
<td>63.76</td>
<td>63.4</td>
<td>64.2</td>
<td>0.22</td>
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<tr>
<td>80.0% Angular Width at 0.0° (deg)</td>
<td>50.9</td>
<td>50.87</td>
<td>50.7</td>
<td>51.1</td>
<td>0.08</td>
<td>125.0</td>
<td>132.0</td>
</tr>
<tr>
<td>80.0% Angular Width at 90.0° (deg)</td>
<td>48.9</td>
<td>48.73</td>
<td>48.4</td>
<td>49.3</td>
<td>0.24</td>
<td>126.0</td>
<td>132.0</td>
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<tr>
<td>90.0% Angular Width at 0.0° (deg)</td>
<td>40.8</td>
<td>40.73</td>
<td>40.6</td>
<td>40.8</td>
<td>0.05</td>
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<tr>
<td>90.0% Angular Width at 90.0° (deg)</td>
<td>35.1</td>
<td>34.79</td>
<td>34.4</td>
<td>35.1</td>
<td>0.18</td>
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<tr>
<td>Angle Ratio at 5.0% Width</td>
<td>1.00</td>
<td>1.005</td>
<td>1.00</td>
<td>1.01</td>
<td>0.001</td>
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<tr>
<td>Angle Ratio at 13.5% Width</td>
<td>1.01</td>
<td>1.004</td>
<td>1.00</td>
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<td>0.001</td>
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<tr>
<td>Angle Ratio at 50.0% Width</td>
<td>1.02</td>
<td>1.019</td>
<td>1.01</td>
<td>1.03</td>
<td>0.004</td>
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<tr>
<td>Angle Ratio at 80.0% Width</td>
<td>1.04</td>
<td>1.044</td>
<td>1.03</td>
<td>1.05</td>
<td>0.006</td>
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<td>Angle Ratio at 90.0% Width</td>
<td>1.16</td>
<td>1.171</td>
<td>1.16</td>
<td>1.18</td>
<td>0.006</td>
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<tr>
<td>Angular Centroid at 0.0° (deg)</td>
<td>-1.6</td>
<td>-1.60</td>
<td>-1.6</td>
<td>-1.6</td>
<td>0.01</td>
<td>62.0</td>
<td>66.0</td>
</tr>
<tr>
<td>Angular Centroid at 90.0° (deg)</td>
<td>-0.1</td>
<td>-0.05</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.04</td>
<td>62.0</td>
<td>66.0</td>
</tr>
<tr>
<td>Angular Peak at 0.0° (deg)</td>
<td>5.0</td>
<td>4.92</td>
<td>4.7</td>
<td>5.2</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular Peak at 90.0° (deg)</td>
<td>1.1</td>
<td>0.63</td>
<td>0.0</td>
<td>1.1</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centroid Amplitude at 0.0° (a.u.)</td>
<td>0.87</td>
<td>0.867</td>
<td>0.86</td>
<td>0.87</td>
<td>0.000</td>
<td></td>
<td></td>
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<tr>
<td>Centroid Amplitude at 90.0° (a.u.)</td>
<td>0.99</td>
<td>0.892</td>
<td>0.89</td>
<td>0.90</td>
<td>0.002</td>
<td></td>
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<tr>
<td>Peak Amplitude at 0.0° (a.u.)</td>
<td>0.89</td>
<td>0.885</td>
<td>0.89</td>
<td>0.89</td>
<td>0.000</td>
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</tr>
<tr>
<td>Peak Amplitude at 90.0° (a.u.)</td>
<td>0.90</td>
<td>0.899</td>
<td>0.90</td>
<td>0.90</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude for Theta = 0.0° at 0.0° (a.u.)</td>
<td>0.88</td>
<td>0.878</td>
<td>0.88</td>
<td>0.88</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude for Theta = 0.0° at 90.0° (a.u.)</td>
<td>0.99</td>
<td>0.895</td>
<td>0.89</td>
<td>0.90</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude for Theta = 45.0° at 0.0° (a.u.)</td>
<td>0.05</td>
<td>0.051</td>
<td>0.05</td>
<td>0.06</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude for Theta = 45.0° at 90.0° (a.u.)</td>
<td>0.05</td>
<td>0.048</td>
<td>0.04</td>
<td>0.05</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LD 8900 Goniometric Radiometer

Sample Data: LED Device
LD 8900 Goniometric Radiometer
VCSEL Measurement
LD 8900R Goniometric Radiometer
Sample Data: VCSEL
LD 8900R Goniometric Radiometer

VCSEL Modes @ 7, 15, 19, 24, 29 mA
LD 8900R Goniometric Radiometer
Sample Data: Single-Mode Fiber
LD 8900HDR Goniometric Radiometer

Far-Field Profile Data:
Single-Mode Fiber
LD 8900HDR Goniometric Radiometer

3D Far-Field Profile Data: Single-Mode Fiber

200 Azimuthal Scans in ~1 Hour
Conventional techniques require 200 hours (5 weeks)
LD 8900HDR Goniometric Radiometer

Far-Field Profile Data:
Dispersion-Shifted Fiber
LD 8900HDR Goniometric Radiometer

3D Far-Field Profile Data: Dispersion-Shifted Fiber
Scanning Goniometric Radiometer

MFD vs Wavelength

250 Measures At Each Wavelength:
1 Man-Year Labor Using Conventional Goniometer
1 Man-Day with New Scanning Goniometer Technique

Mode-Field Diameter (µm) vs Wavelength (nm)
Near Field Characterization

Applications

- Fibers - MFD, $A_{\text{eff}}$
- LDs - Modes, Geometry
- VCSELs - Modes Geometry
- Waveguides - Modes, Geometry
- Tapered Fibers - Spot Size
- Quantum Dots - Modes, Geometry
- Other “μm-subμm” structures
Direct Near-Field Source Measurement Techniques

Camera/Magnifying Objective
- Diffraction Limited for \( \mu m \)-sub\( \mu m \) Structures
- NA, MTF, and \( \lambda \) Dependence of Optics
- Access to Aperture Field

Scanning Knife-Edge
- Access to Aperture Field

Near Field Scanning Optical Microscopy (NSOM)
- Speed of Measurement
- Access to Aperture Field
- Expensive
Indirect Near-Field Characterization from Far-Field Measurement

- Calculate Near Field quantities from measured Far Field
- Minimal Optics Limitations
- No Access Constraints
- Ease of Measurement
- Provides “sub-μm” Measures
Indirect Near-Field Characterization from Far-Field Measurement

Fiber MFD
  Petermann II Integral

Fiber $A_{\text{eff}}$
  Hankel Transform of Far-Field Power

Diffraction Limited $1/e^2$ “Spot” Size
  Calculated from Far-Field Divergence ($d=4\lambda/\pi\theta$)
  Account for $M^2$: $d=4M\lambda/\pi\theta$

Aperture Field
  2D Fourier Transform Methods
Far-Field Measurement of Mode-Field Diameter of Optical Fiber

TIA/EIA FOTP-191  Direct Far-Field Method
“Reference Method”

Petermann II Integral:

\[
MFD = \left(\frac{\lambda}{\pi}\right) \sqrt{\frac{2 \int_{-\theta}^{\theta} I(\theta) \sin(\theta) \cos(\theta) d\theta}{\int_{-\theta}^{\theta} I(\theta) \sin^3(\theta) \cos(\theta) d\theta}}
\]
# Far-Field/Near-Field Measurements of Focused Laser Beam Spot Size

<table>
<thead>
<tr>
<th>Lens</th>
<th>Axis</th>
<th>Measurement Technique</th>
<th>&quot;Times Diffraction Limit&quot; Width (µm)</th>
<th>MFD (µm)</th>
<th>1/e² Width (µm)</th>
<th>1/e² Width (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Horizontal</td>
<td>Goiometric Radiometer</td>
<td>5.46</td>
<td>5.22</td>
<td>5.52</td>
<td>5.67</td>
</tr>
<tr>
<td>1</td>
<td>Vertical</td>
<td>Objective Lens/CCD Camera</td>
<td>5.68</td>
<td>5.35</td>
<td>5.93</td>
<td>6.25</td>
</tr>
<tr>
<td>2</td>
<td>Horizontal</td>
<td>XY Slit Profiler</td>
<td>6.00</td>
<td>5.64</td>
<td>5.96</td>
<td>6.33</td>
</tr>
<tr>
<td>2</td>
<td>Vertical</td>
<td></td>
<td>5.93</td>
<td>5.65</td>
<td>6.34</td>
<td>6.36</td>
</tr>
</tbody>
</table>
## Far-Field/Near-Field Measurements of Edge-Emitting Laser Diode

<table>
<thead>
<tr>
<th>Device</th>
<th>Axis</th>
<th>Measurement Technique</th>
<th>Far Field</th>
<th>Near Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Goniometric Radiometer</td>
<td>100x Objective Lens/Camera</td>
</tr>
<tr>
<td>Laser Diode</td>
<td>&quot;Fast&quot;</td>
<td>&quot;Diffraction Limit&quot; Width</td>
<td>1.20 (µm)</td>
<td>1.10 (µm)</td>
</tr>
<tr>
<td>Laser Diode</td>
<td>&quot;Slow&quot;</td>
<td>2D Fourier Transform</td>
<td>1.11 (µm)</td>
<td>3.20 (µm)</td>
</tr>
</tbody>
</table>
Far Field/Near Field
VCSEL Mode @ 7mA
Far Field/Near Field
VCSEL Mode @ 15mA
Far Field/Near Field
VCSEL Mode @ 19mA
Far Field/Near Field
VCSEL Mode @ 24mA
Far Field/Near Field
VCSEL Mode @ 29mA
**Scanning Goniometric Radiometer**

**Summary**

New Technique Provides:

- **Measurement Speed and Accuracy**
  - Single Scans in Real Time
  - 3D Profiles with Resolution Better than CCDs
  - Angular Sampling Resolution to 0.001°

- **Wide Angular FOV**
  - w/ fold mirror ... approaching 180°
  - w/o fold mirror ... up to 360°

- **Single Detector**
  - No calibration issues
High Dynamic Range
  - Up to >100 dB Optical Power Range

Ease of Use
  - Compact System
  - Use like a Power Meter—simply point and measure
  - Operates in any orientation
  - Source can be stationary; e.g. wafer level testing

Wide Applicability

In Conclusion, a REVOLUTIONARY Technique!!
Thank you!