RadTech Conference
Orlando, FL
May 9-11

Superior Reliability and Performance

W r i g h t
W a y
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Photodiode-free Radiometry for UV LED Arrays

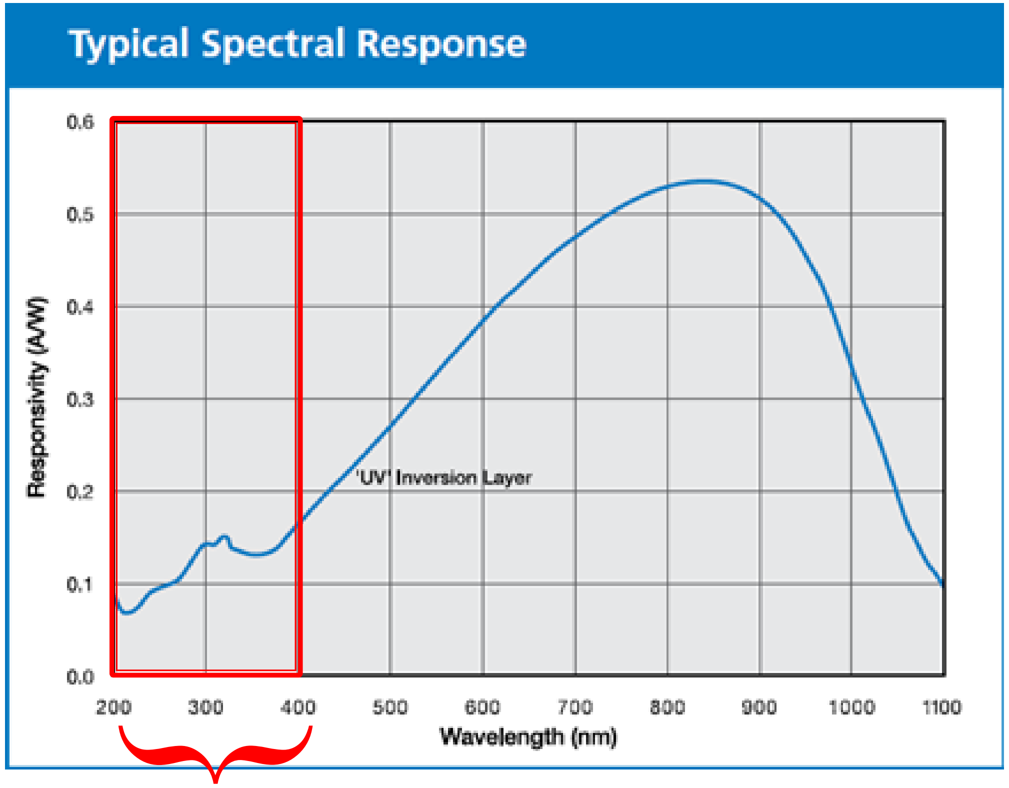
Dr. Robin E. Wright
Wright Way UV Consulting LLC

Conventional UV Radiometers

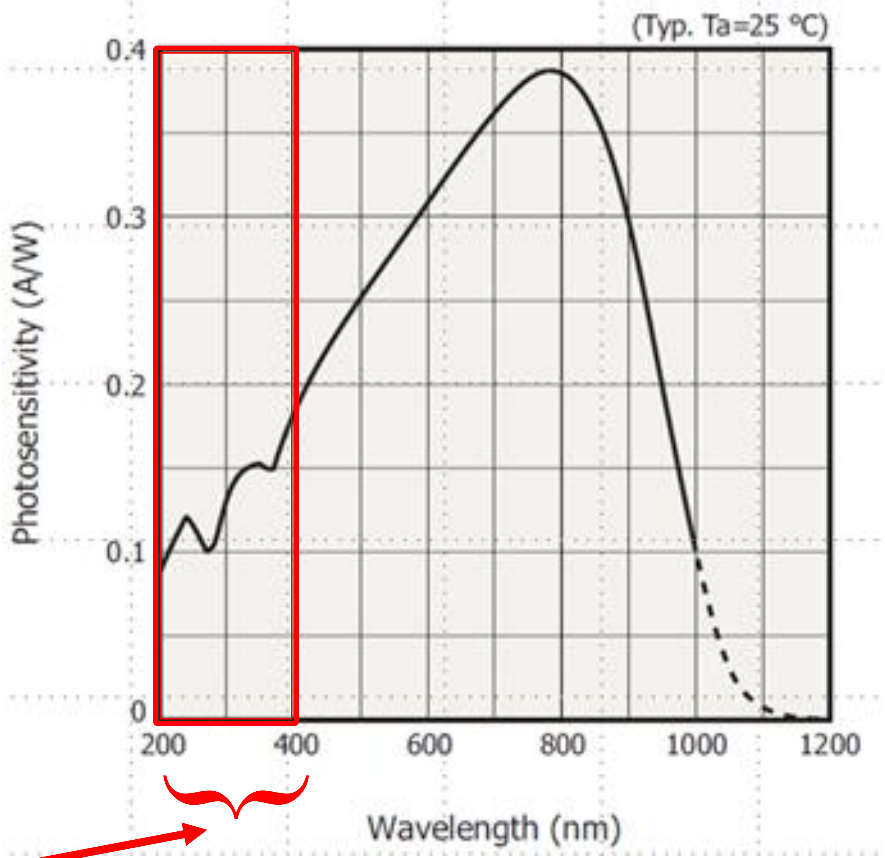
- UV radiometers use Si photodiodes to measure UV radiation
    - Fast response time
    - Good linearity
    - Saturate at high power
    - Sensitivity degrades with UV exposure
    - Spectral responsivity decreases as temperature increases
    - Spectral responsivity is strongly dependent on wavelength
    - **Calibration recommended every 6-12 months**

Representative Spectral Photoresponsivity Curves

Company A



Company B



200-400 nm

International Commission on Illumination

Taken from the CIE Home Page (cie.co.at)

The International Commission on Illumination […] is devoted to worldwide cooperation and the exchange of information on all matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology.

[…] Since its inception in 1913, the CIE has become a professional organization and has been accepted as representing the ***best authority on the subject*** and as such is recognized by ISO [International Organization for Standardization] as an ***international standardization*** body.

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

2-87: Broadband UV LED radiometric measurements between 320 nm and 420 nm

Standard LED sources with different peak wavelengths (colours) and a standard broadband LED measurement procedure will be worked out to perform uniform, fast, and low-uncertainty radiometric LED measurements. **In contrast to existing spectral detector-response based standards (where LEDs are measured with large errors)**, the procedure is based on a standardized LED and the spectral product (signal) of the standardized LED distribution and the spectral responsivity of the standardized LED measuring reference radiometer. The standardized LED integrated radiance or the integrated irradiance from it and also the integrated responsivity of the reference radiometer can be determined. The reference scale will be propagated with the reference radiometer to field radiometers to perform one-step LED (broadband radiance or irradiance) measurements. The measurements can be applied for all kinds of LEDs and/or groups of different LEDs. Chair: George Eppeldauer (NIST)

Key Notes from CIE 2-87 Mission Statement

- "standardized LED distribution" –
  - Current LED arrays are identified by a central wavelength designation, i.e., a 395 nm array may contain chips with peak emissions ranging from about 390 to about 400 nm. So, what does standardized mean here?
- "spectral responsivity of the standardized LED measuring reference radiometer" –
  - Photodiode-based spectral responsivity curves vary by manufacturer and can change by as much as 5% or more over a 10 nm range (spectral range of individual chip emission maxima in an array). Since photodiode spectral responsivity curves can vary dramatically, again, what does standardized mean?

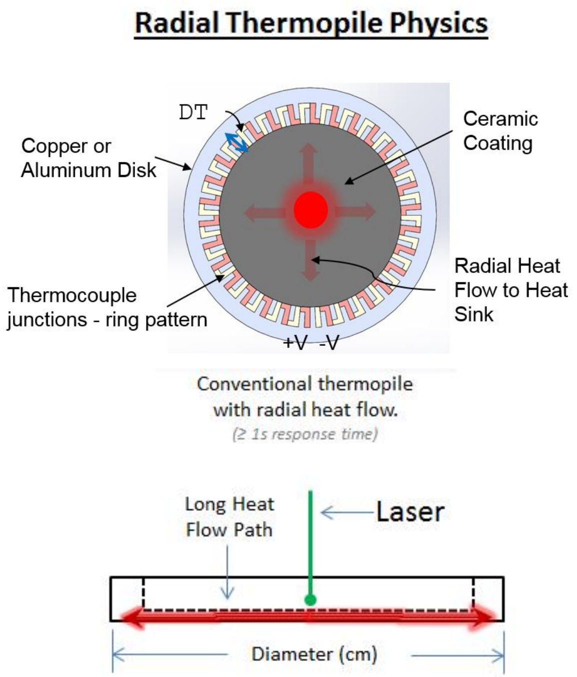
Thermoelectric Detectors

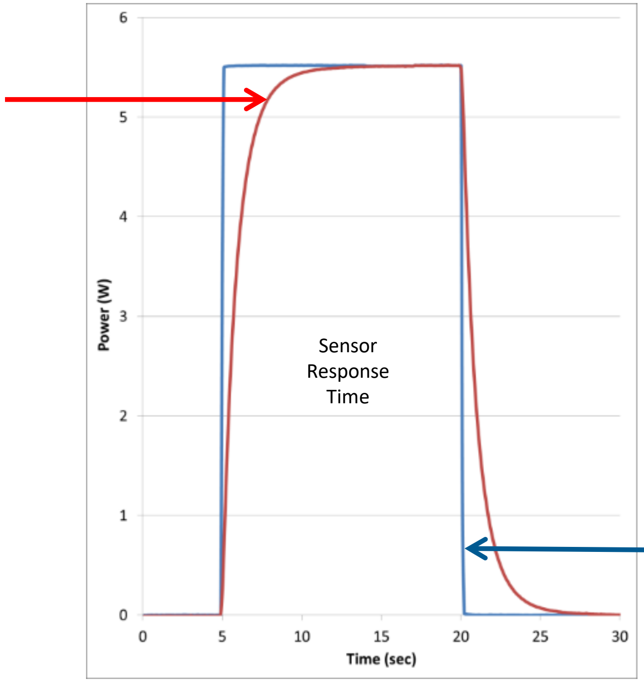
A Better Solution for UV LEDs

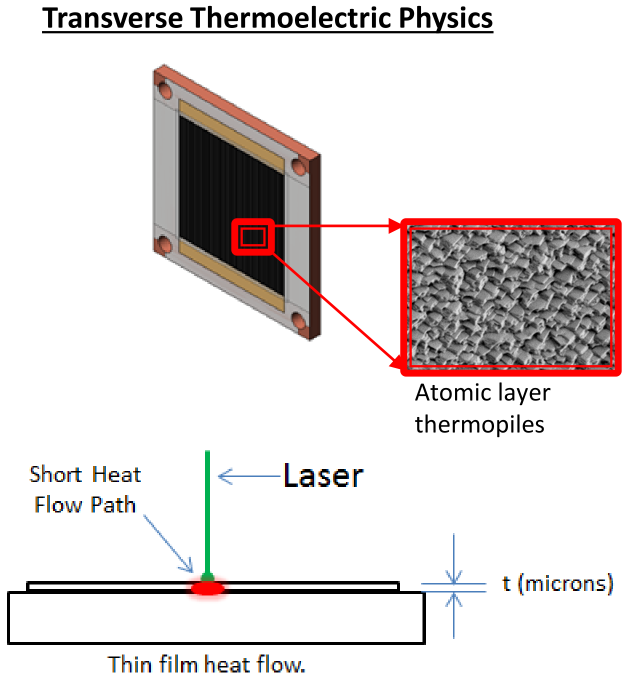
- LEDs are pseudo-monochromatic sources
  - If I use a 365 nm LED array, I don't need to worry about filtering out other wavelengths since the LED peak outputs are confined to a narrow bandwidth (ca. 10 nm)
  - Visible light may be an issue if the LED array peak power is less than ~100 mW/cm^2
- Thermopiles are thermoelectric devices that convert thermal energy into electrical energy
  - Based on Seebeck Effect discovered in 1821; first thermopile made by Nobili ca. 1829
  - Output is proportional to a local temperature difference or gradient
  - Relatively flat spectral response
  - High saturation threshold
  - Slow response time
  - Sensitive to ambient temperature changes

Coherent PowerMax Pro vs. Conventional Thermopile

Coherent, Inc. has patented a new, high speed power sensor for lasers







$t_{rise} \propto (Diameter)^2$

$t_{rise} \propto (Thickness)^2$

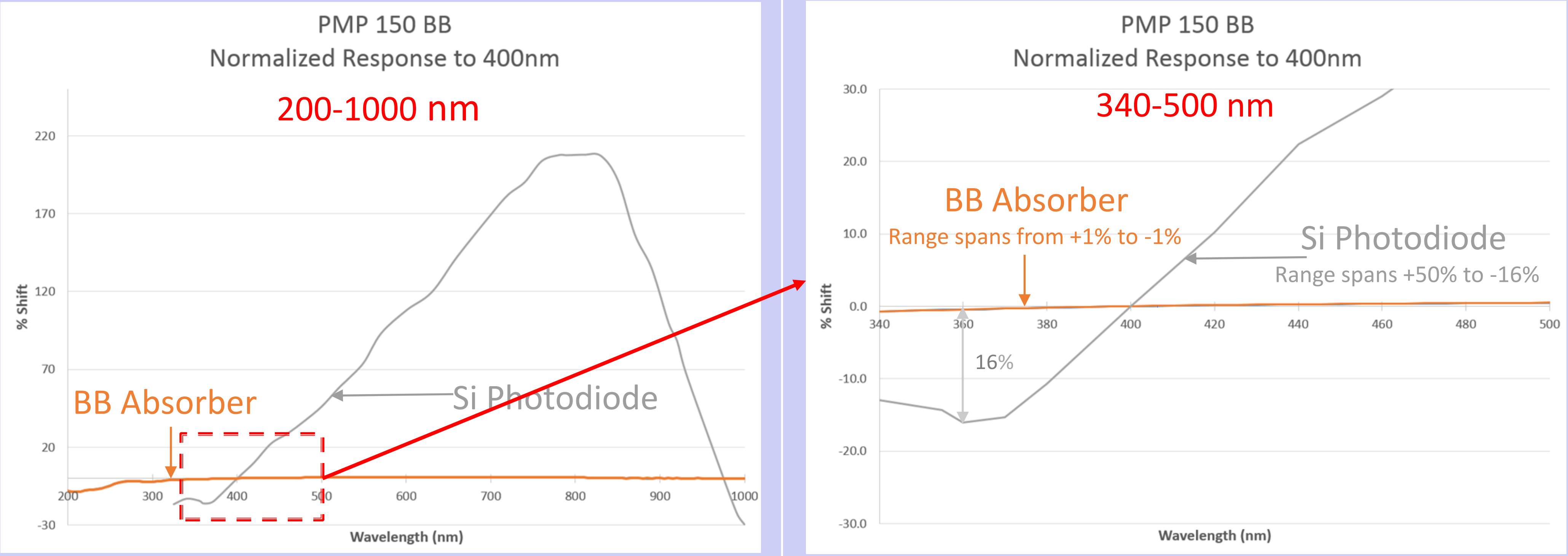
Short heat flux path equates to fast response time creating new possibilities in laser **and LED** measurement

- Blackbody coating allows accurate and repeatable measurements

Spectral Response Comparison

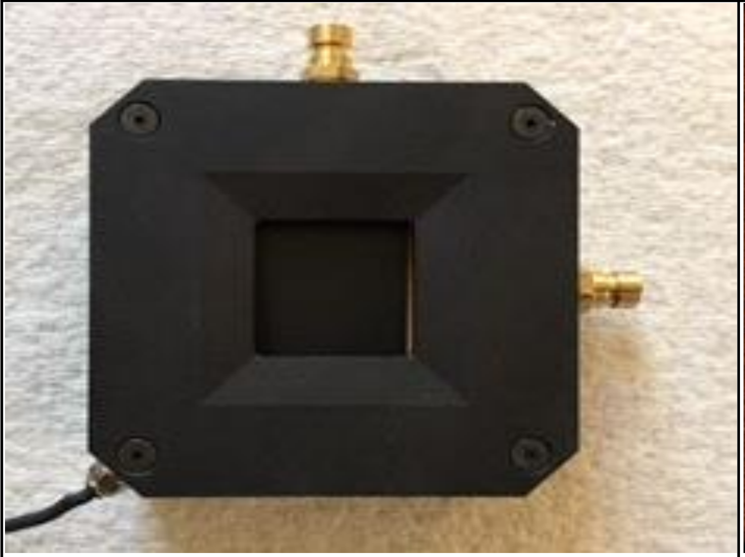
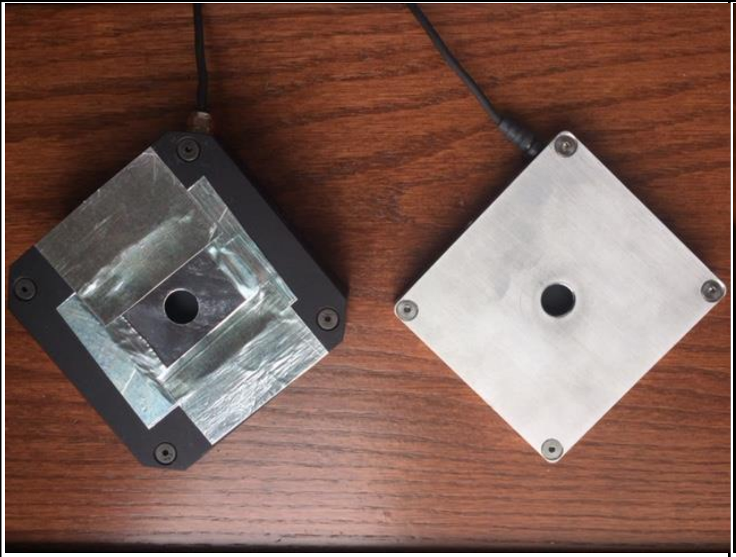
Data provided by Guang Li, Coherent

Responsivity Curves Normalized at 400 nm

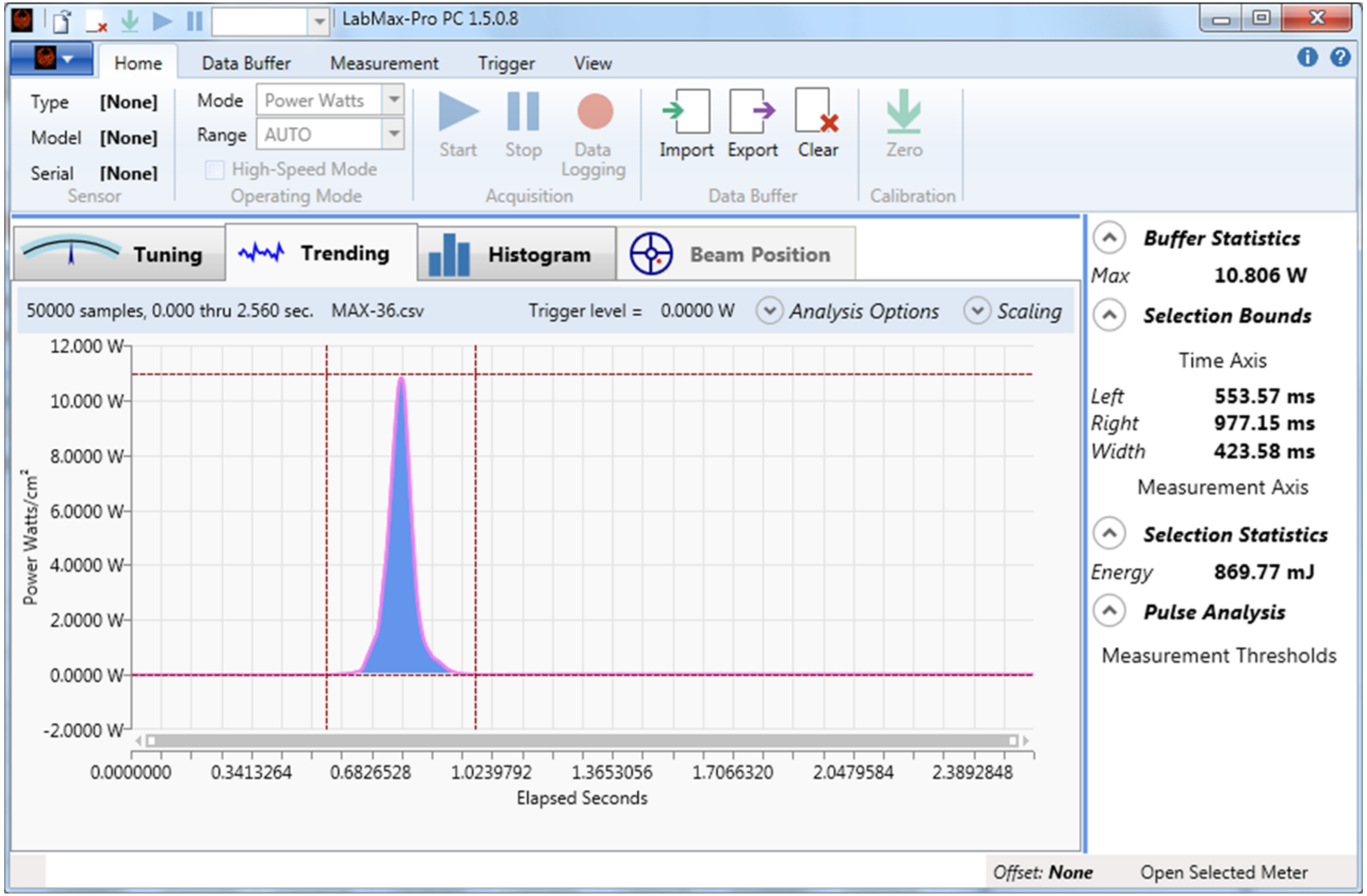


Evolution of a Better Profiling Radiometer

Initial trials using the Coherent meter as a profiling radiometer were done at 3M

GEN 1 (2015)		GEN 2 (2017)
		
Blackbody (BB) absorber in laser power meter	BB original and low profile sensor with 1.0 cm^2 apertures	Edge view of LP and original heads (height = 13 mm vs. 30 mm)

Feasibility Studies (3M, 2015)



Single Pass Video
GEN 2 low-profile sensor (3M, 2017)

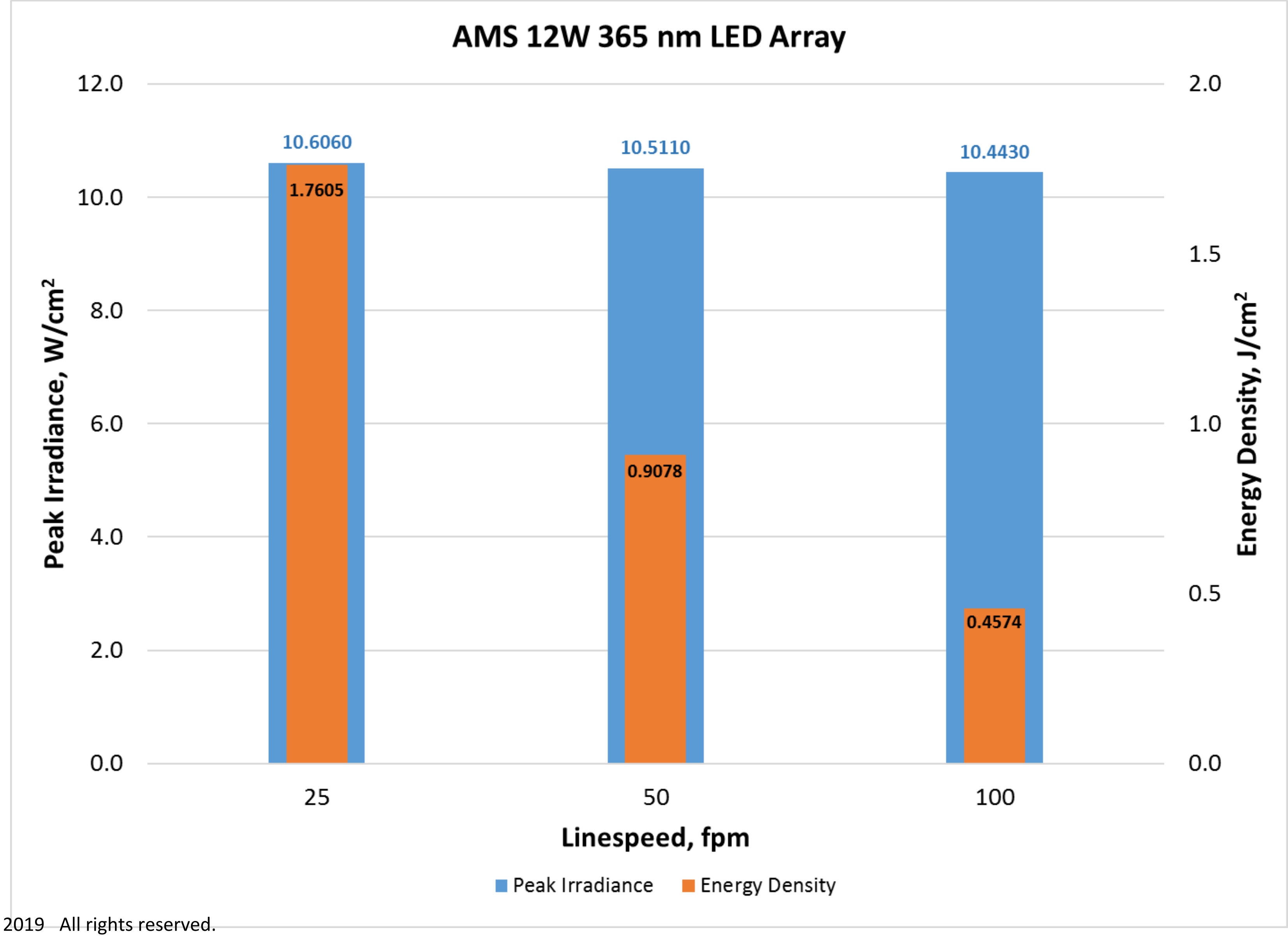
Source is an LED flashlight

Setup:

- Trigger = 10 mW
- Pre-trigger = 1000
- Buffer capacity = 10000
- Sampling rate = 20 kHz

X-axis is time; Y-axis shows irradiance

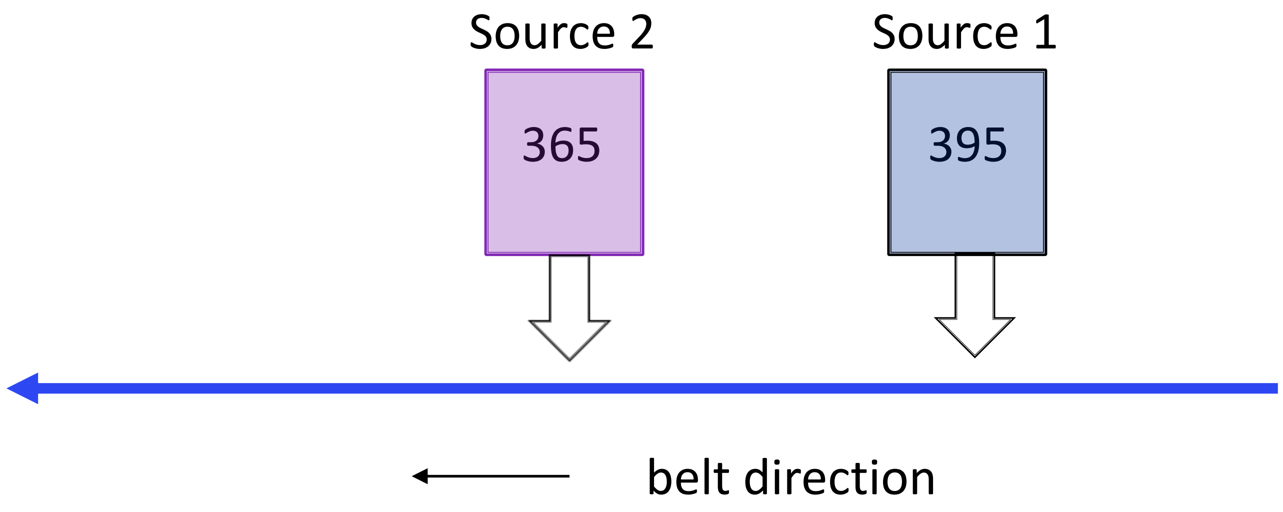
Thermoelectric Sensor as a Profiling Radiometer



Two LED Array Studies

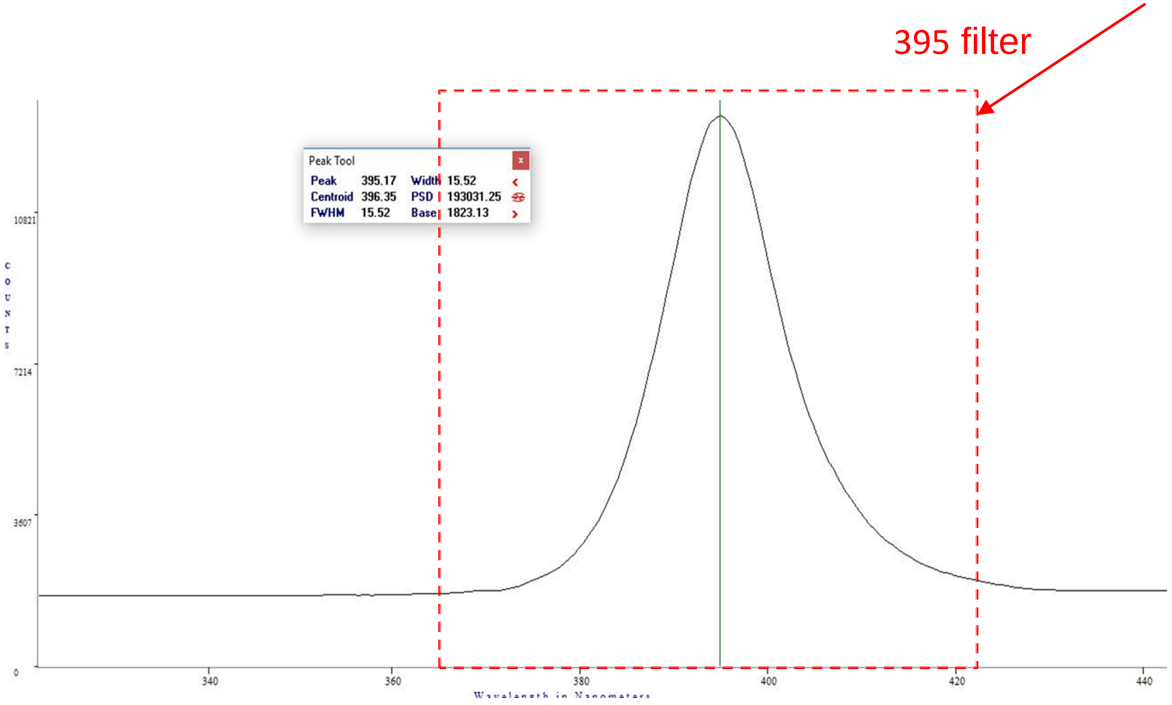
Experiments run at AMS Spectral UV in River Falls, WI

- Comparison made using two different wavelength LED sources
- Study compared the Coherent thermoelectric blackbody sensor against two photodiode-based radiometers using bandpass filters

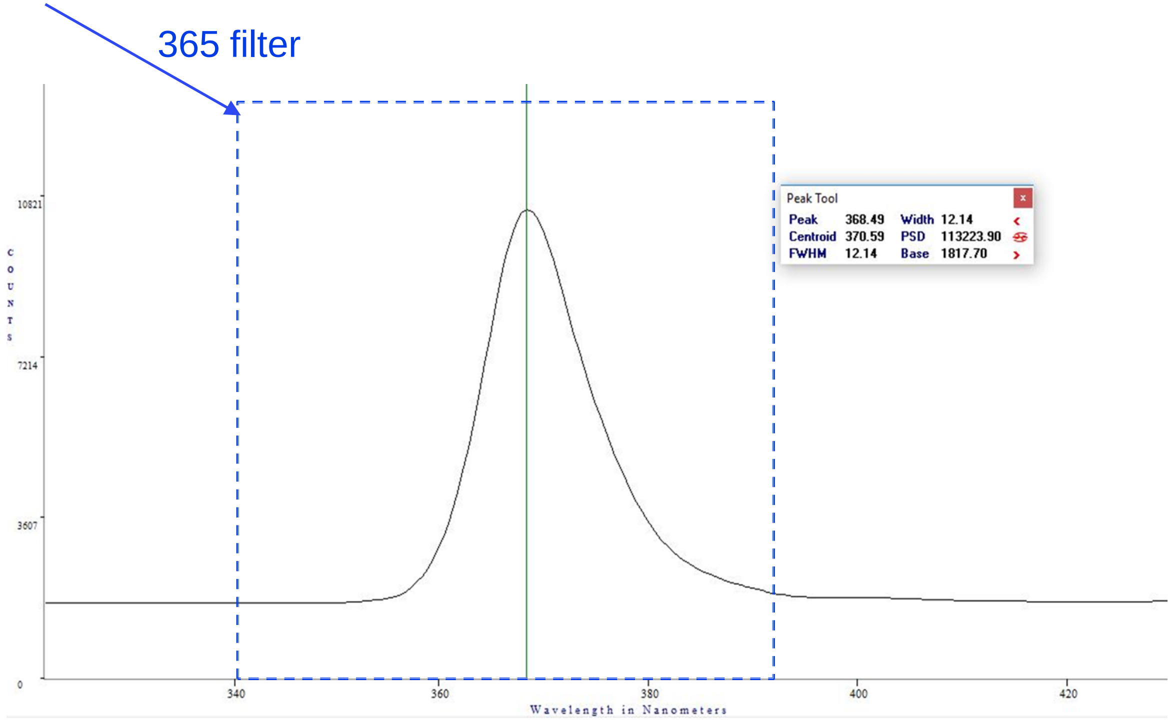


Source Emission Spectra

Comparative bandpass filter windows



Source 1 @395 nm

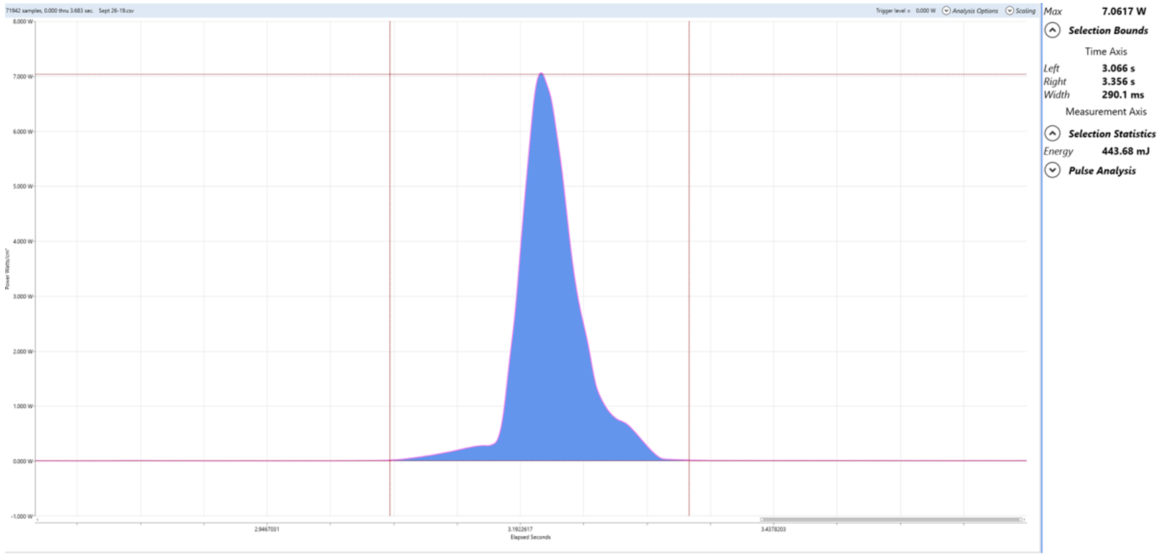


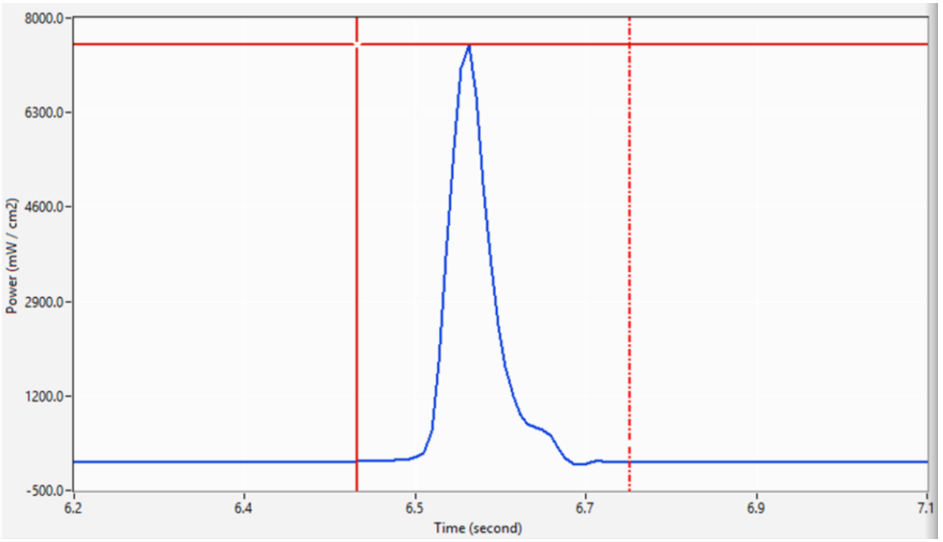
Source 2 @368 nm

Experimental Conditions

- Conveyor speed fixed at 30 fpm
- Lamp powers set to 50%
- Three measurements taken at each run condition
    - Used the low profile, tethered Coherent PMP and commercial filter-based comparative radiometers
    - Cursors were used to determine energies using a fixed exposure time for each source
- Distance from base of source to surface of radiometers was kept constant

Comparison Scans under Source 1 (395 nm)

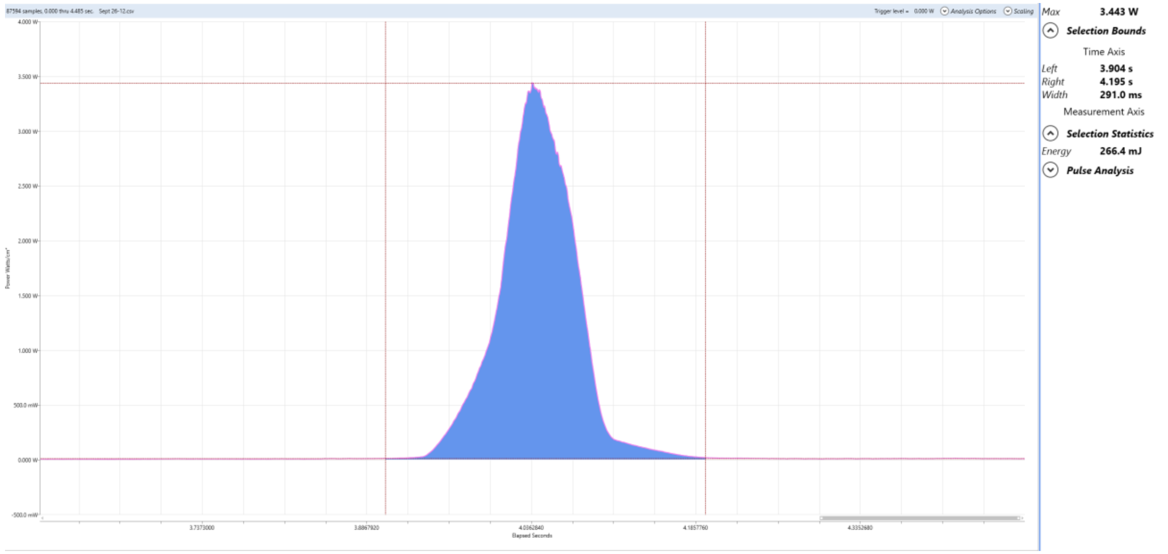


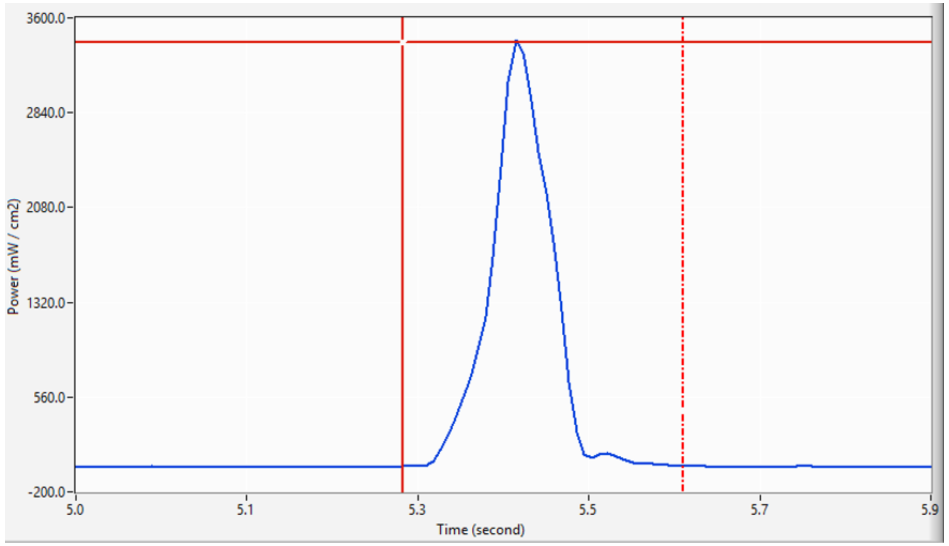


Average of 3 Runs	Coherent PMP
Peak irradiance, W/cm^2	7.05
Energy density, mJ/cm^2	443.3

Comparative (395)
7.49
386.8

Comparison Scans under Source 2 (368 nm)

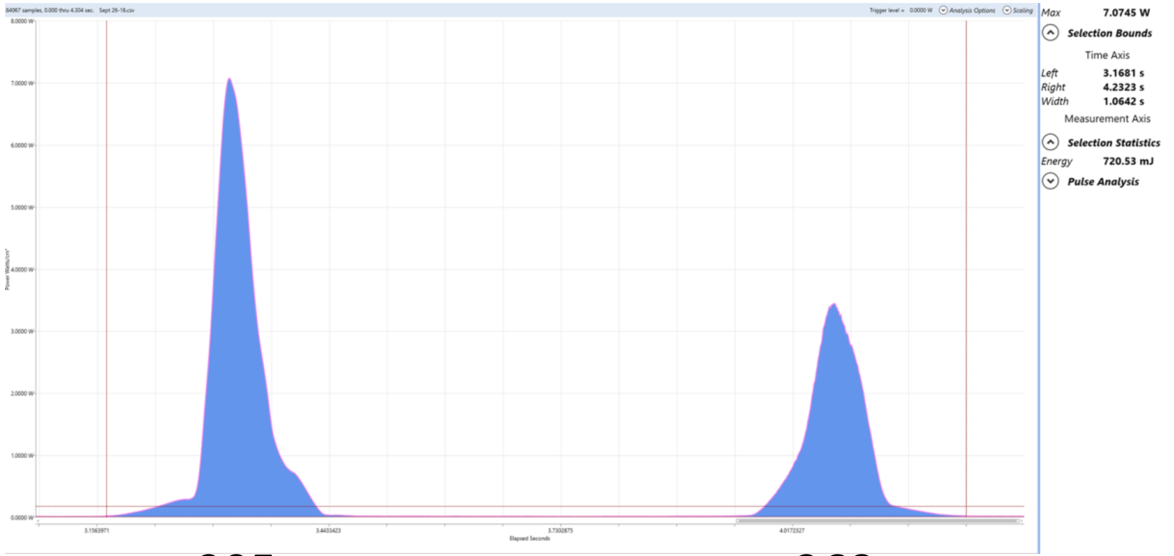




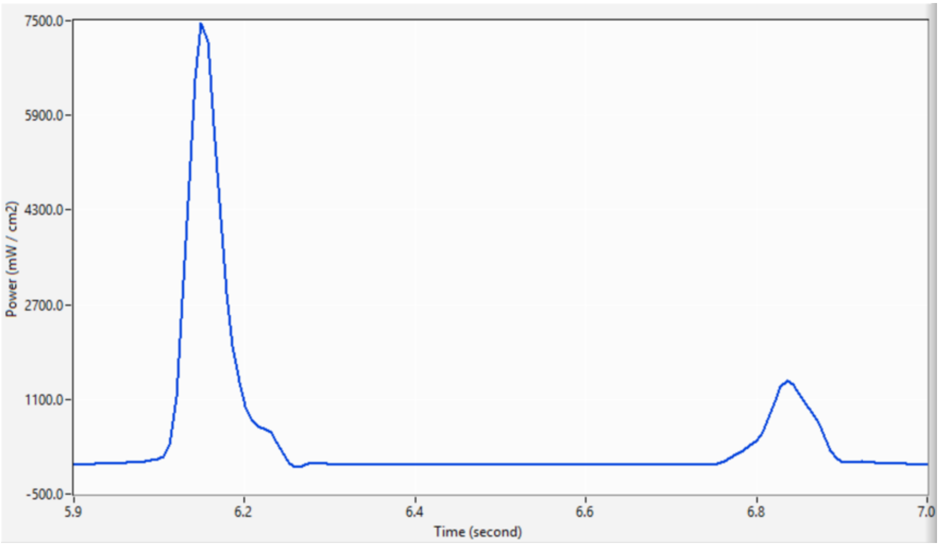
Average of 3 Runs	Coherent PMP
Peak irradiance, W/cm^2	3.45
Energy density, mJ/cm^2	265.1

Comparative (368)
3.41
229.0

Comparison using Sources 1 (395) and 2 (368) nm



395 368



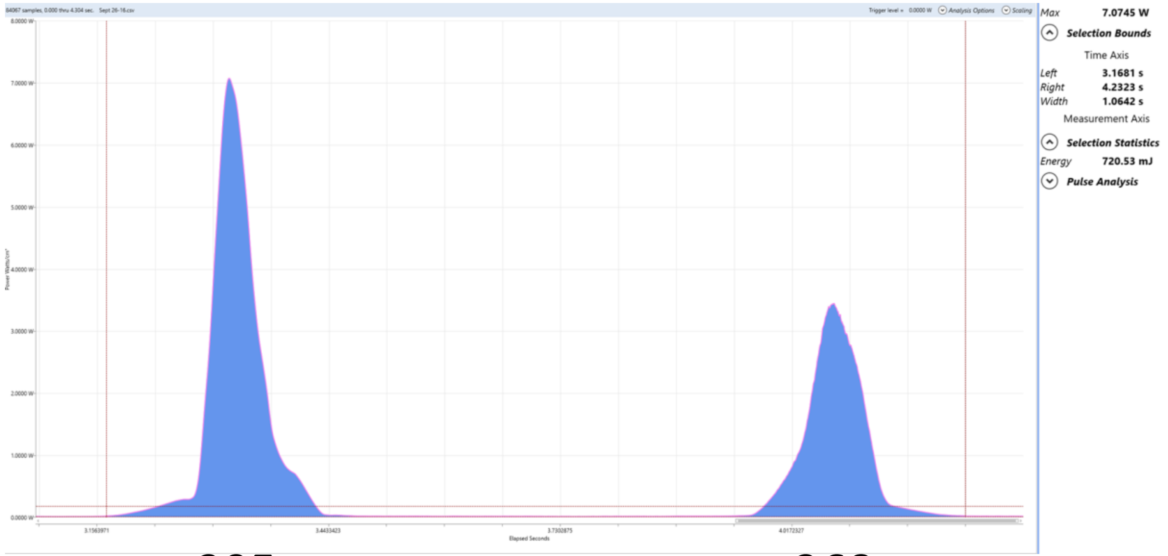
395 368

Average of 3 Runs	Coherent PMP
Peak irradiance, W/cm^2	7.07 (7.05)
Energy density, mJ/cm^2	720.5 (708.4 = sum of 395 and 368)

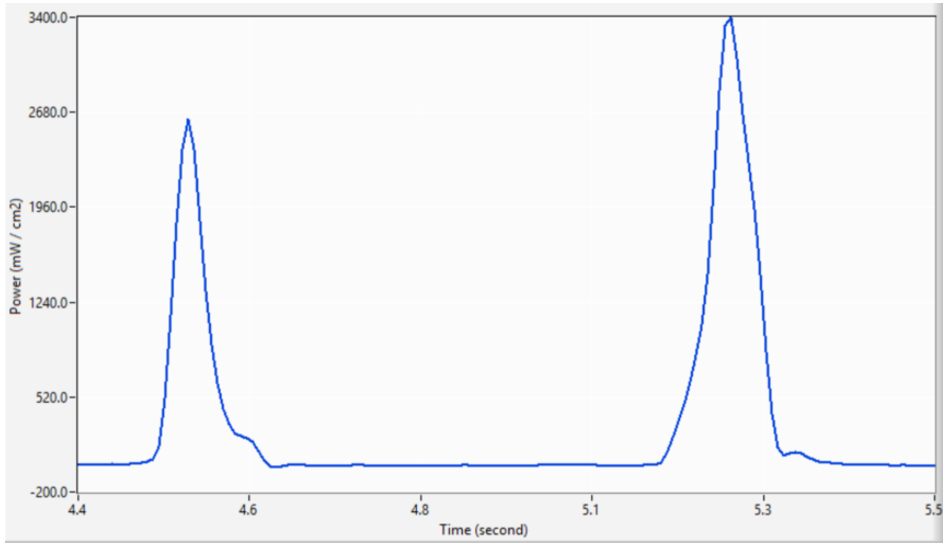
Comparative (395)*
7.48 (7.49)
479.7 (386.8)

*Values in parentheses were data using only the 395 nm source

Comparison using Sources 1 (395) and 2 (368) nm



395 368



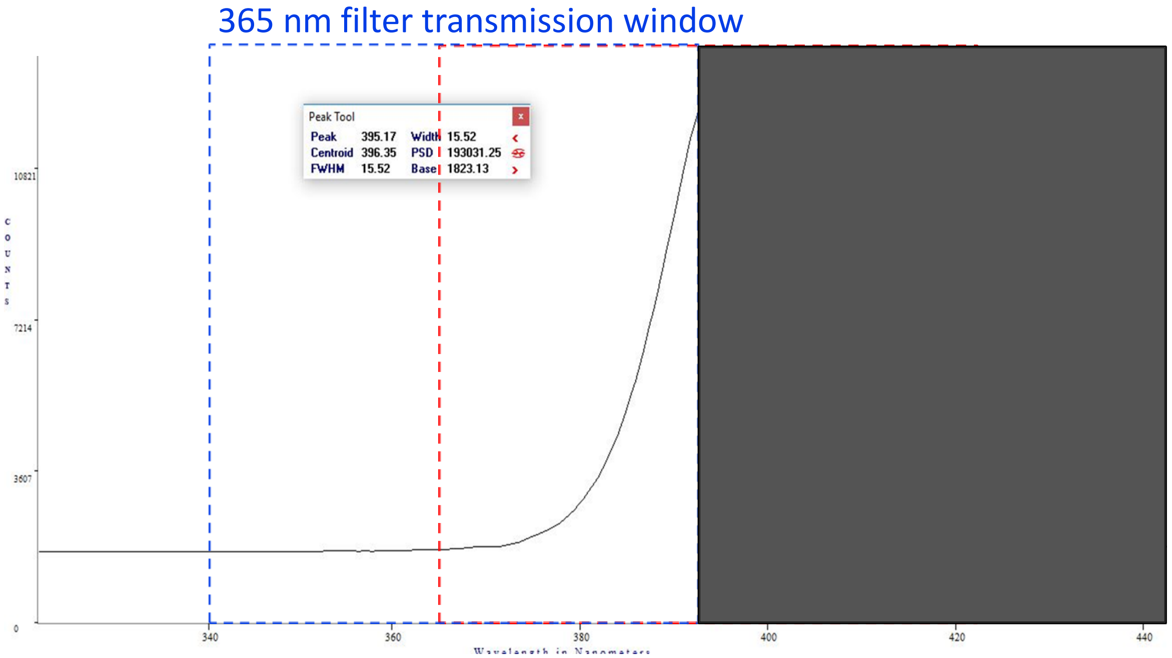
395 368

Average of 3 Runs	Coherent PMP
Peak irradiance, W/cm^2	7.07 (3.45)
Energy density, mJ/cm^2	720.5 (708.4 = sum of 395 and 368)

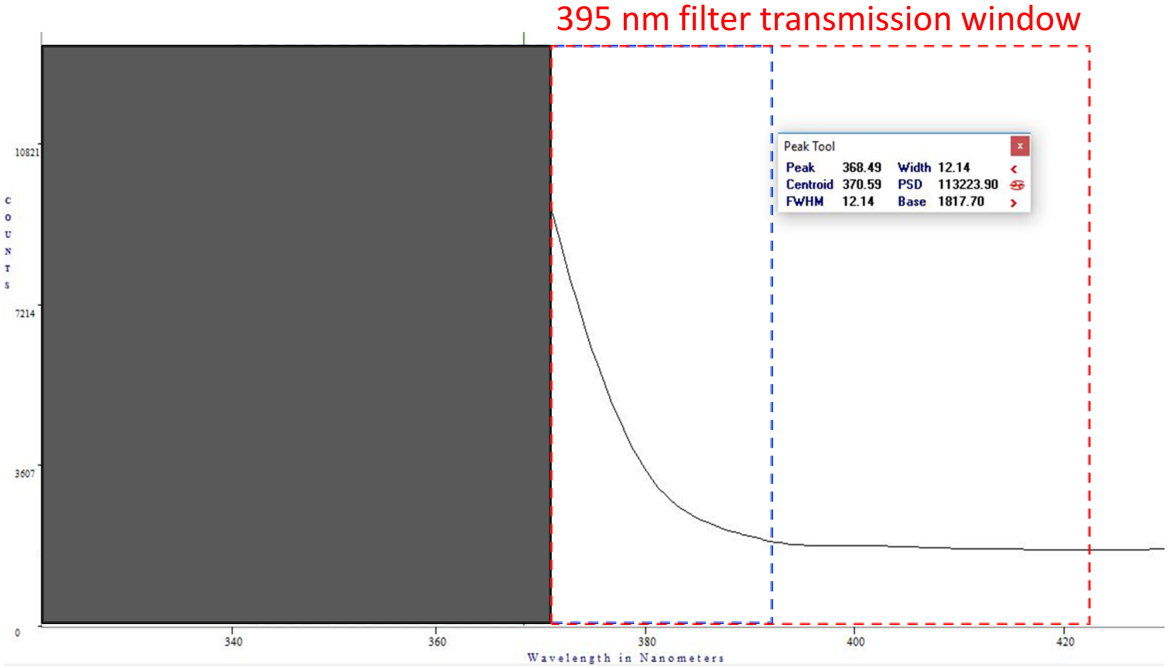
Comparative (365)*
3.41 (3.41)
362.0 (229.0)

*Values in parentheses were data using only the 368 nm source

Filter Overlap with LED Emission Bands



Source 1 @395 nm



Source 2 @368 nm

Conclusions from Study

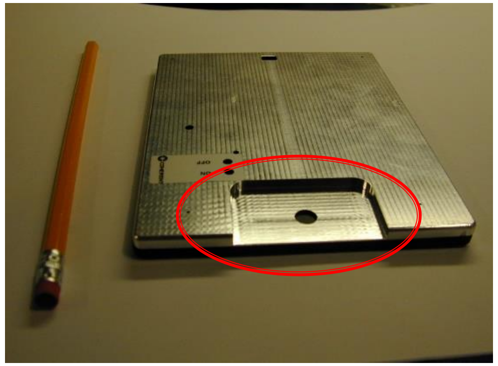
- Thermoelectric sensor sees two independent sources and calculates the total energy (mJ/cm^2) correctly
- Comparative filter-based devices see and record both sources due to filter leakage of the off-wavelength source (i.e. 368 through 395 filter)
  - Peak irradiance reported depends on the relative source outputs and the magnitude of the secondary wavelength leakage
  - <u>Energy density is not reported accurately</u>

IMPORTANT NOTE - If $\Delta\lambda$ of sources were greater, filter overlap with filter-based devices would diminish and differences should become negligible

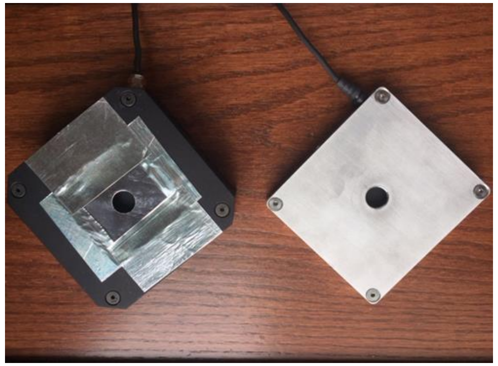
GEN 3 Cordless Thermoelectric Sensor

Experiments run at AMS Spectral UV in River Falls, WI

- Blackbody sensor area reduced to 15x15 mm
- Differences between the GEN 3 cordless and GEN 2 LP sensor was <2%
  - Cordless prototype was built using a shell from another prototype
  - Tethered low-profile device (13 mm height) was 2 years old and used a 30x30 mm sensor with a 1.0 cm^2 aperture while cordless device used the new 15x15 mm sensor with a 0.51 cm^2 aperture



Prototype cordless sensor
Height of sensor reduced to ca. 8 mm

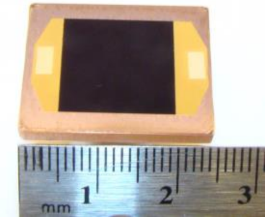


Tethered sensors
Original (30 mm) and low-profile (13 mm) sensors

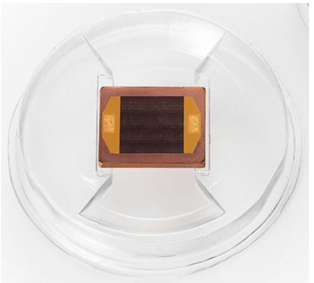
Summary

- Cohrent's PowerMax Pro technology for measuring LED irradiance and energy density has now been demonstrated using a **thin**, **cordless** sensor
  - 225 mm^2 active area (15x15 mm)
  - Data uploads as *.csv file using current PMP software or Excel

Laser power sensor



PMP sensor
(metric reference ruler)



Packaged PMP sensor

Coherent, Inc.

LSM (Laser Systems & Measurement) Business Unit and LMC (Laser Measurement & Control) Product

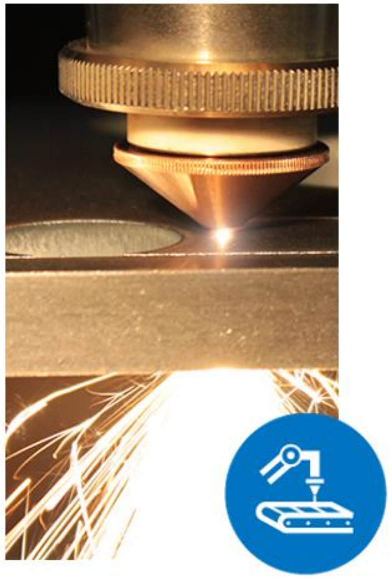
COHERENT – The Photonics Company

Provider of Photonics Solutions - Primarily Lasers for Commercial and Scientific Research Applications

- Founded in 1966
- Core Markets

OEM Components & Instrumentation

Microelectronics



Materials Processing

Scientific Research & Government Programs

Wilsonville, OR USA

Laser Systems and Measurement

Laser Measurement, Diode Lasers

Microelectronics	Material Processing	OEM Components and Instrumentation	Scientific Research and Government Programs
●	●	●	●

Site:

Space: 41,000 ft^2

Employees 112

Key Technologies

Multi-wavelength laser diode modules, structured light lasers, power, energy and beam diagnostic instruments

Products

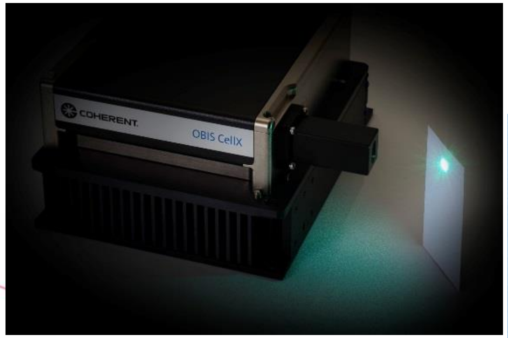
OBIS Family, Sting Ray, Laser Measurement and Control

Applications

Life Science, Machine Vision, Measurement and Industrial Control

Quality certifications

ISO 9001 certified and ISO 17027 certified



Wilsonville, OR USA

Laser Measurement, Diode Laser Applications

Life Sciences Wavelength and power scaling ability opens the possibility for new applications	**Instruments** Laser power & energy measurement devices for system integrators, in-field laser personnel and laboratory users	**Structured Light** Laser line generators and pattern generators used in inspection for manufacturing and production industries
		
Flow Cytometry	Scientific	Manufacturing
Confocal Microscopy	Materials Processing	Food
Genomics	Semiconductor	Pharmaceutical
Proteomics	Life Sciences & Medical	Medical
Medical Diagnostics		

COHERENT

Laser Measurement Product Line

FieldMate

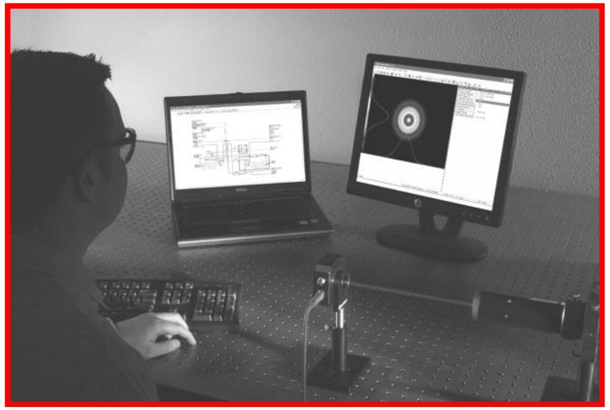
FieldMaxII

LabMax

- Wide range of sensors covers most laser applications
  - Thermopiles and optical sensors
  - Pyroelectric sensors
  - Meters and instrumentation
  - PowerMax-Pro transverse thermoelectric sensors – very fast power measurement!

LabMax Pro

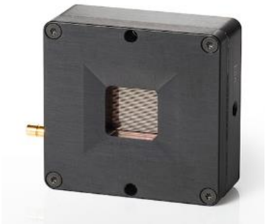
- Beam profile & propagation products



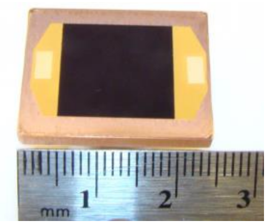
Status of PowerMax Pro (PMP) Profiling Radiometer

- Coherent’s markets are based on lasers and laser technologies
  - They have no customers or experience in the UV curing area
  - They have no sales force in the area
  - As a result,

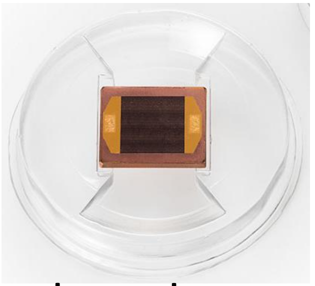
Coherent is seeking to work with an OEM partner to commercialize the PMP



Laser power sensor



Current PMP sensor



Packaged sensor