Additive Manufacturing of a Solid-State Lighting Fixture

John Trublowski – Eaton Corporation
Indika Perera – Lighting Research Center, Rensselaer Polytechnic Institute
With Ethan Shen – Xerox Research Centre of Canada
August 24-25, 2021

Acknowledgement: U.S. Dept. of Energy: EERE

- Acknowledgment: “This material is based upon work supported by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) under the Solid-State Lighting Program Award Number DE-EE0008722.”

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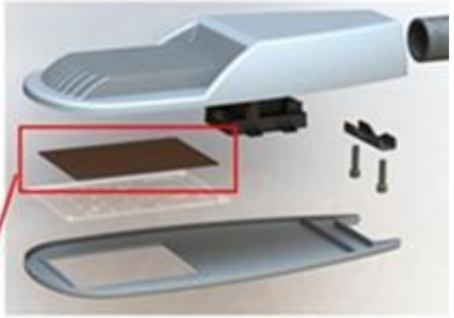
Luminaire Assemblies: Where do we want to be?

Integrated Roadway Concept

Eaton Concept Prototype (2017)*

- Fully printed, integrated circuitry with LED, driver, sensors and antennas
- Minimal part count
- Simplified assembly



Integrated Manufacturing Flow

Fully Integrated CAD Design → Machine Download and Debug → Manufacture AM Luminaire → Post Process → Test → Inventory → Ship

Metal Material Resource
Polymer Material Resource
Optical Material Resource
Electronics and Sensor Material Resource

Fully Integrated Manufacturing Approach

- “Print on demand” model
- Few components and assemblies
- Integrated mechanical/electronics

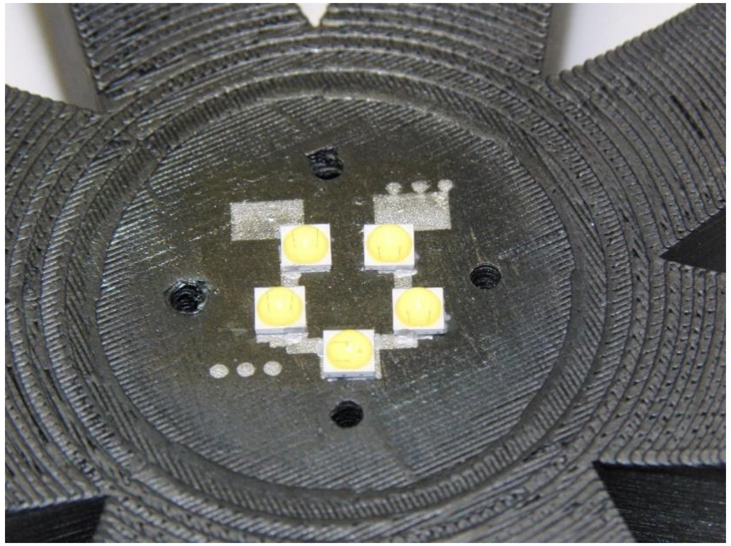
- Reduced operations and mfg. footprint
- Consolidated supply chain
- “Near” zero inventory
- Faster time to market

*** Print-based Manufacturing of Integrated, Low Cost, High Performance SSL Luminaires**, **Final Report,** DoE/SSL Funded Project, **Contract Number: DE-EE0006260, 2016**

Why Additive Manufacturing?: Cost benefits

Key Cost Benefits

- Reduced Design Cycle Time
  - Full digital design
  - CAD to Print Processing
- Tooling Reduction or Elimination
  - Timing for design updates (days vs. months)
  - Tooling storage eliminated (stored in CAD)
- Component Integration
  - Direct printing of electronics (LED circuit, sensors, antennas)
  - Printed fasteners
  - Potential to print heat sinks and reflectors as a single component
- Local (onshore) manufacturing
  - Small, easily configurable Mfg. footprint

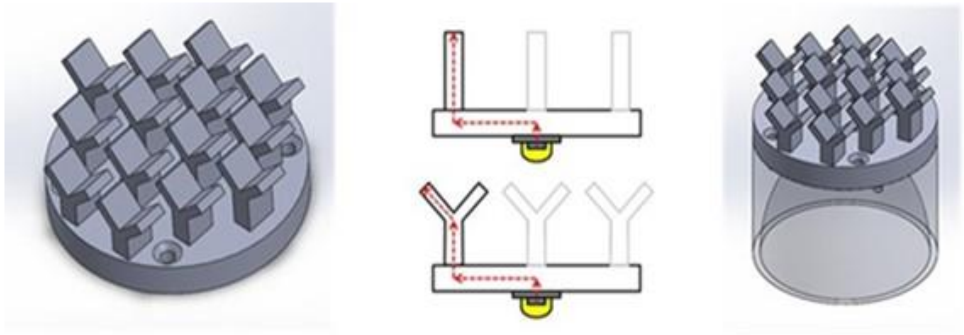


LED Circuit Printed on Thermally Conductive Polymer Heat Sink

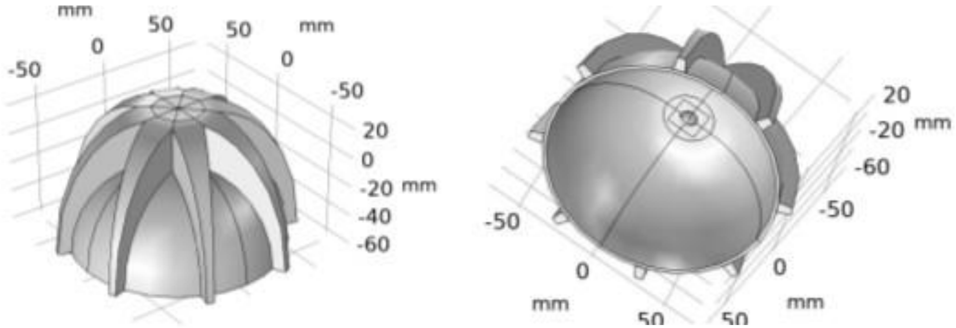
Why Additive Manufacturing?: Design Flexibility

Key Design Benefits

- Unique solutions for thermal, mechanical, optical
  - Exploit and optimize designs without constraints of traditional manufacturing approaches
  - Easy to implement features which are impossible to build using traditional methods (i.e. hollow structures for reducing weight and material)
- Rapid prototypes for concept validation
  - Typically, CAD to Print manufacturing
  - Easy to implement design changes
  - Near Net Shape to minimize post processing
- Integrated structures
  - Easy to combine functions (heat sinking, LED circuitry, mechanical) using printed approaches



Bifurcated ("Y" shaped) Heat Sink



Constructal "Spoke" Heat Sink

Why Additive Manufacturing?: Business Efficiency

Key Benefits for the Business and Customers

- Significant "Time to Market" reduction
  - "Print on Demand" concept
  - Reduce (or eliminate) tooling design and fabrication
- Supply chain consolidation
  - Fewer suppliers
  - Higher quality control on materials
- Reduction in SKU complexity
  - Designs built to order
  - Minimize (or eliminate) inventory
- Custom solutions on a mass production level
  - Easy to implement custom designs
  - Manufacturing is design "agnostic"
  - Lights out manufacturing

Eaton L-PBF printers: EOS M290 and Concept Laser M2 UP1

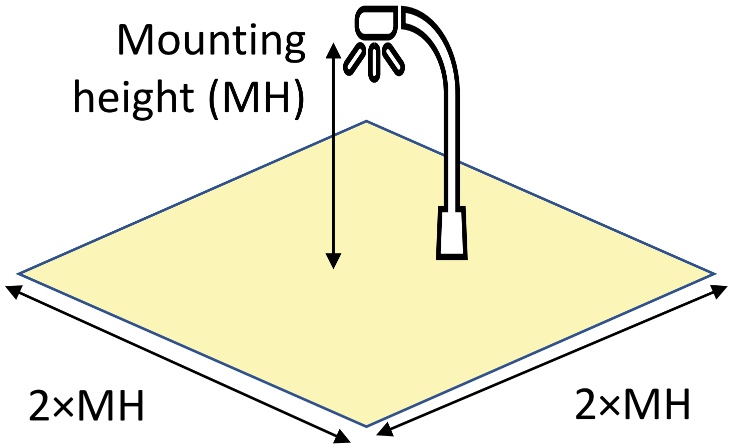
- 400W laser systems
- 10x10x12" build volumes

Technical Approach: System Design and Manufacture

- Optical
  - Reflector design using ray-tracing, measurement setup and characterization
- Thermal
  - Heat sink design and software analysis, measurement of LED case temperature, initial material property characterizations
- Electrical
  - Electrical characterization V, I, P with LED temperature

Prototype luminaire designing and testing

- Designing
  - LED package distribution and layout
  - Reflector design
- Testing
  - Total luminous flux
  - Intensity distribution
  - Illuminance distribution

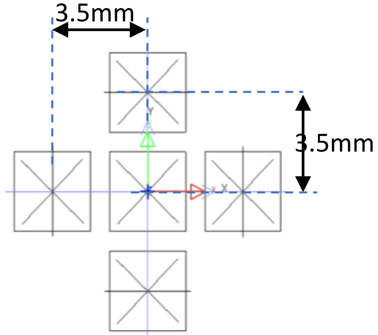


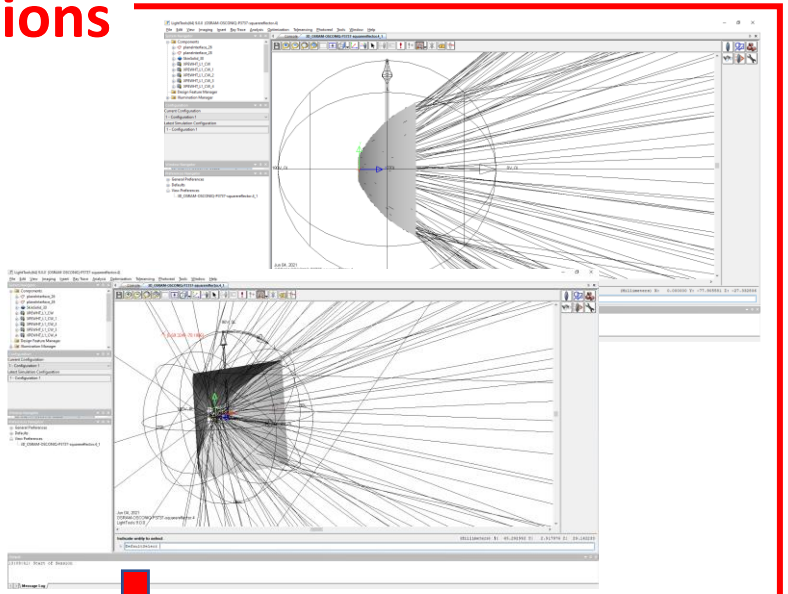
- Electrical characterization of the LED circuits and prototype testing
  - Voltage
  - Current
  - Electrical power (without and with the driver)
  - THD (with the driver)

- Designing
  - Heat sink design
- Testing
  - Thermal power dissipated
  - LED case temperature
  - Heat sink temperature profiles
  - Electrical trace temperature profiles

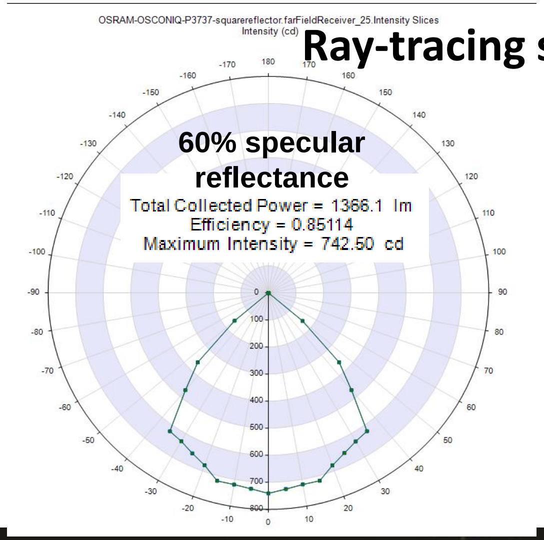
Optical ray-tracing simulations and experiment

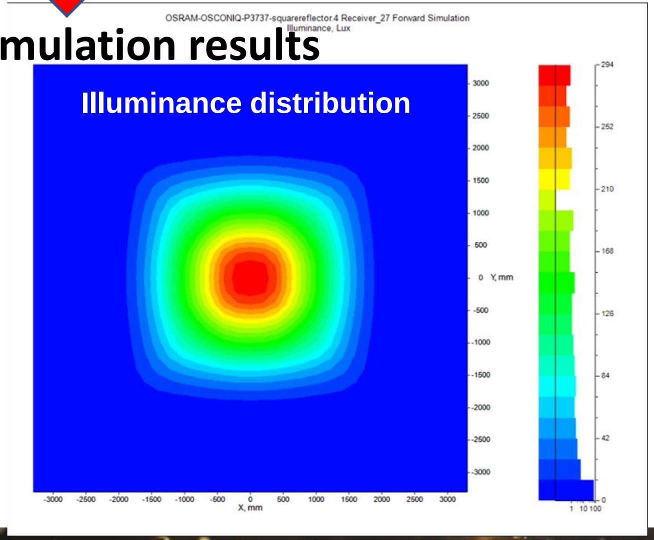
Simulations





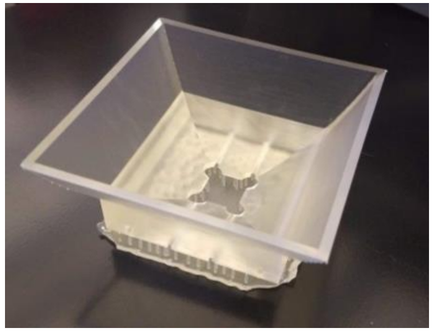
Ray-tracing simulation results





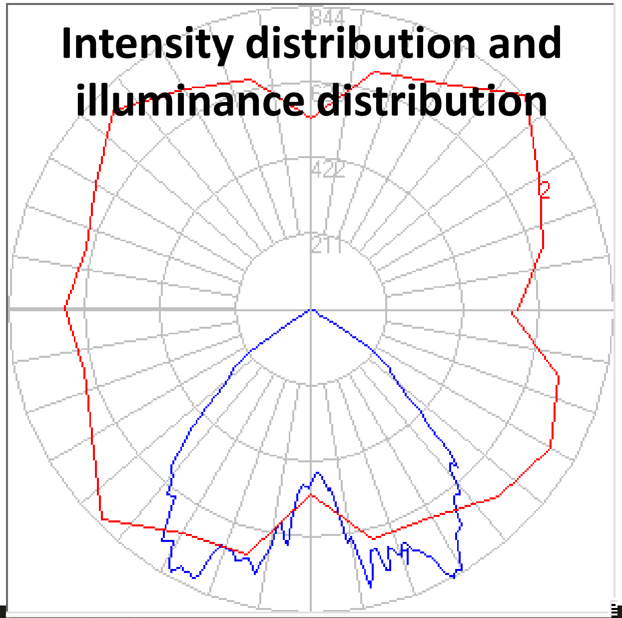
Experiments

SLA 3D printed reflector



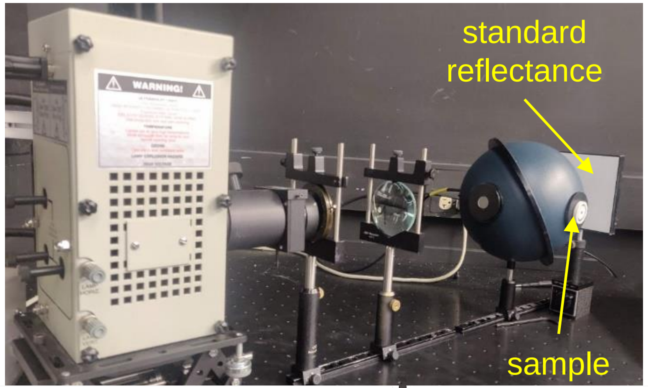
After post-processing and Ni plating

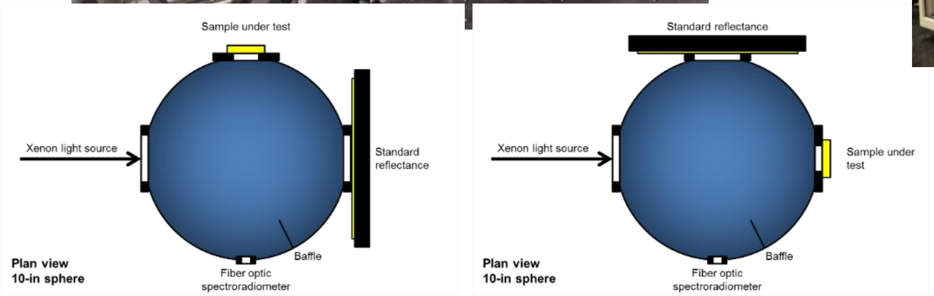
Intensity distribution and illuminance distribution

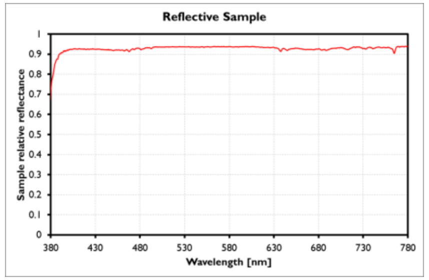


Optical testing

- Reflectance testing of samples





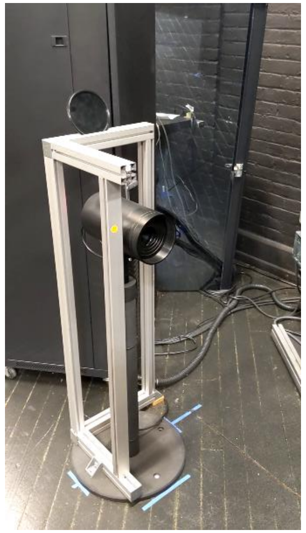


Relative hemi-spherical reflectance

- Prototype testing
  - Luminous flux

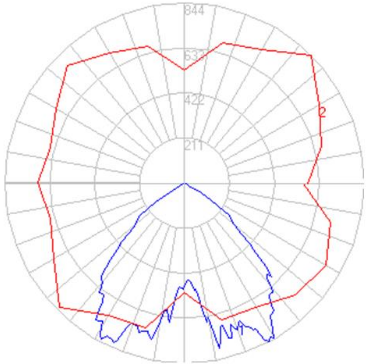
Integrating sphere

- Prototype testing
  - Light distribution



Photometer

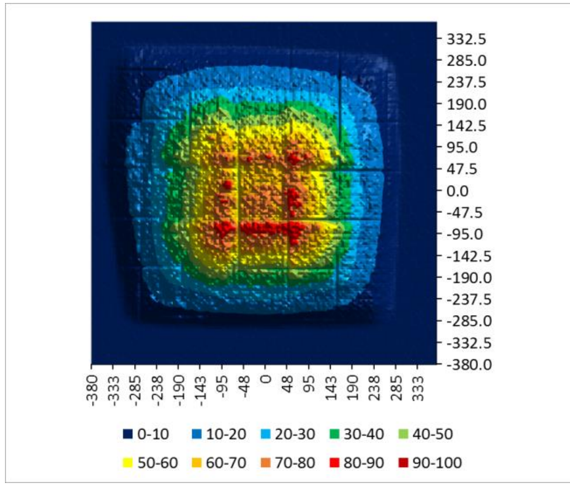
Moving mirror goniophotometer

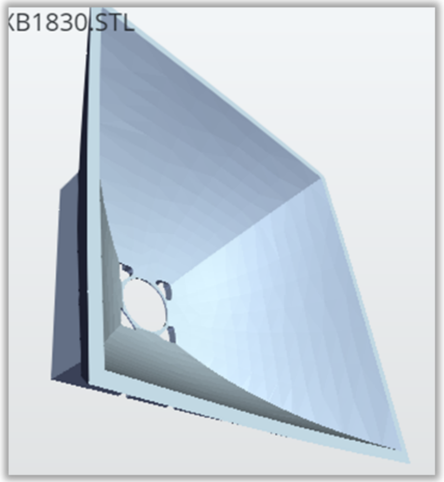


Intensity distribution

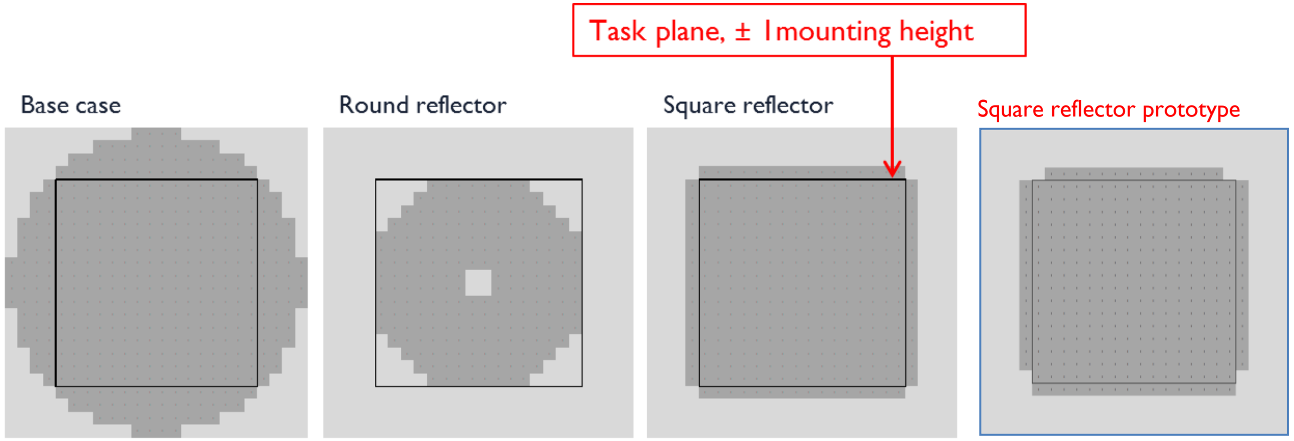
Optical Performance: Application Efficacy

- Simulated several variations of specular reflectors to maximize light falling inside task plane
- 20-ft mounting height
  - 0.5 fc to 7.5 fc
  - Task plane = 2× mounting height (40 × 40 ft square)
- For this design, ~100% of luminaire lumens are inside the task area



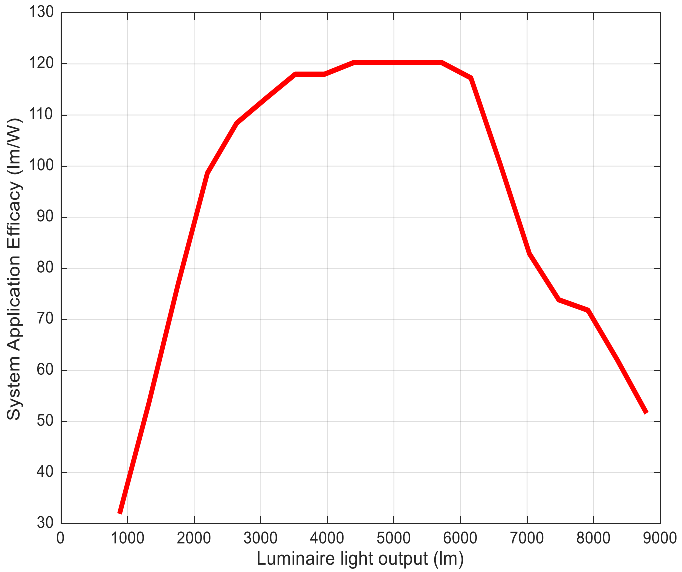


60% reflectance, specular finish
LED efficacy 160 lm/W

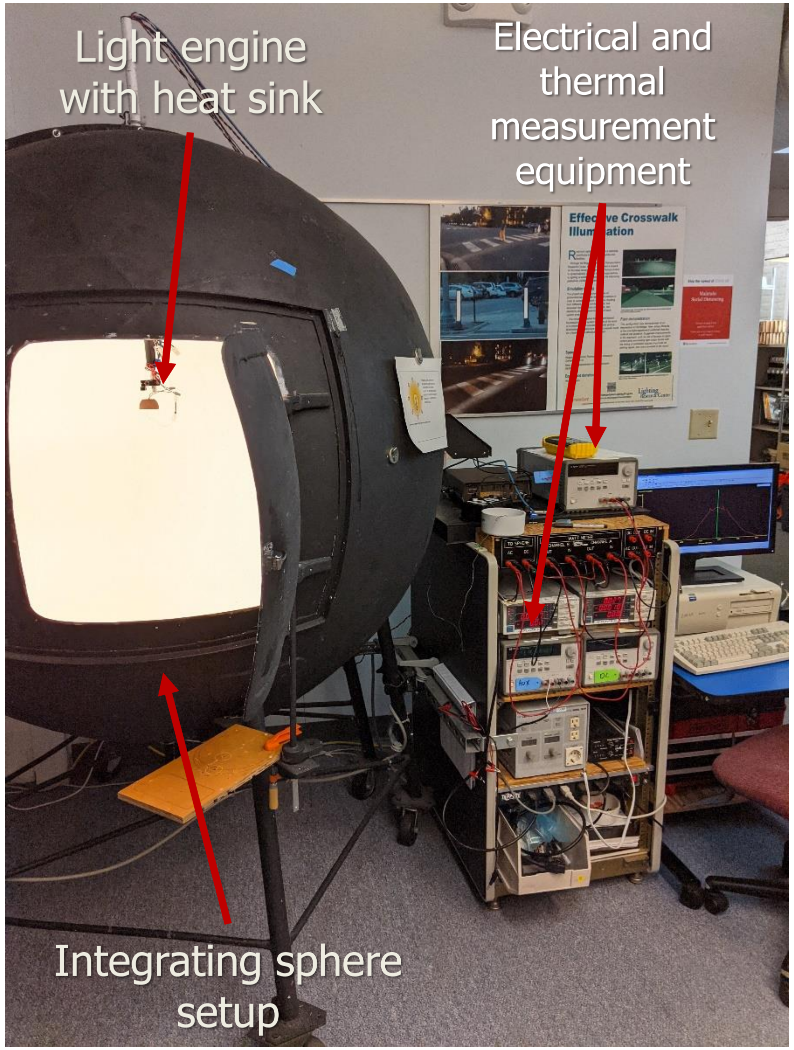


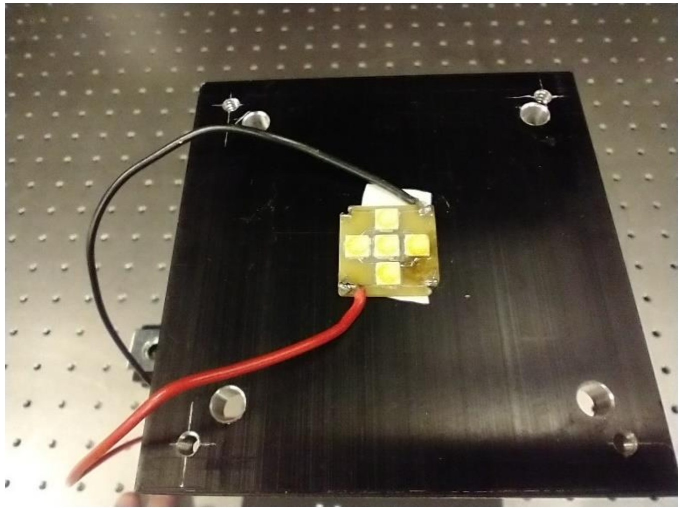
Base case	Round reflector	Square reflector	Square reflector prototype
App Eff = 100 lm/W	App Eff = 73 lm/W	App Eff = 105 lm/W	**App Eff = 120 lm/W**
Coverage 100%	Coverage 83%	Coverage 100%	**Coverage 100%**
22% spill over	2% spill over	9% spill over	**12% spill over**

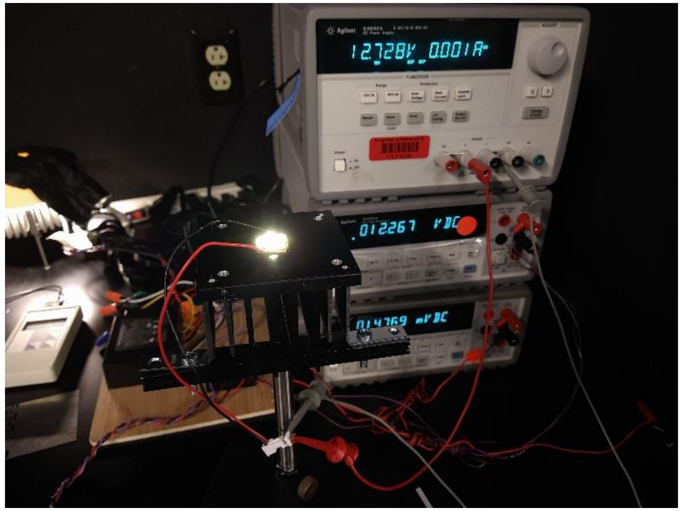
Light gray: cells that do not meet the illuminance requirement

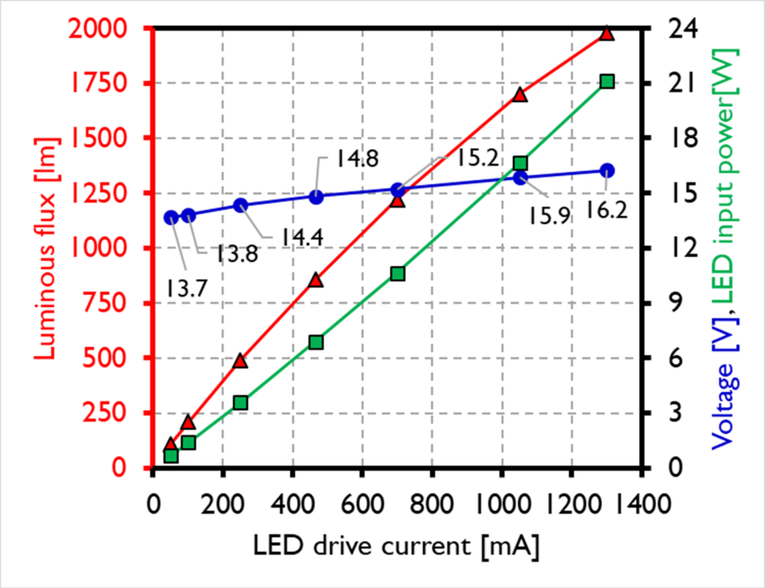


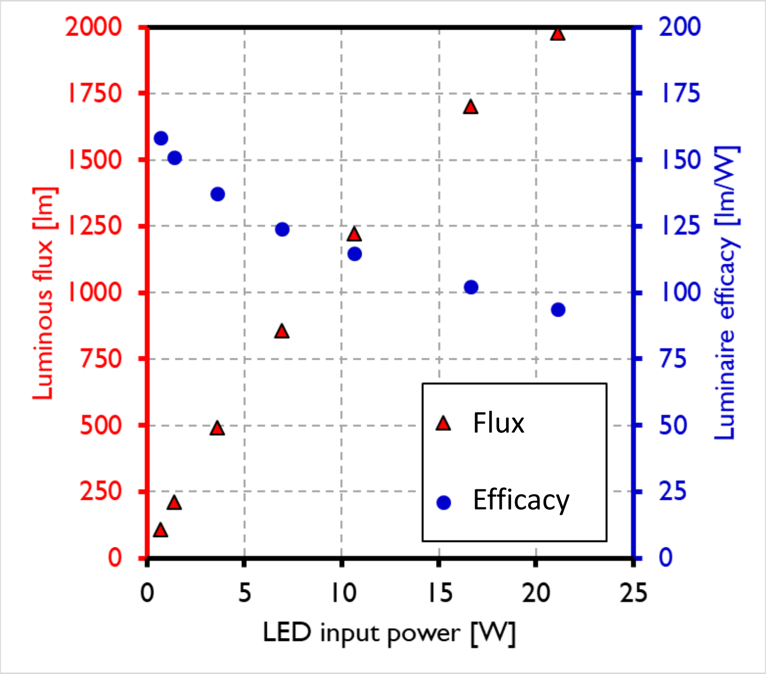
Electrical testing



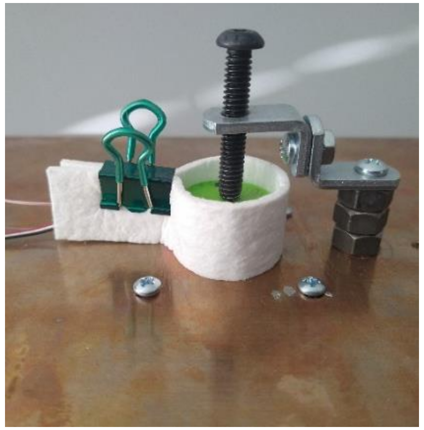








Thermal conductivity testing of samples

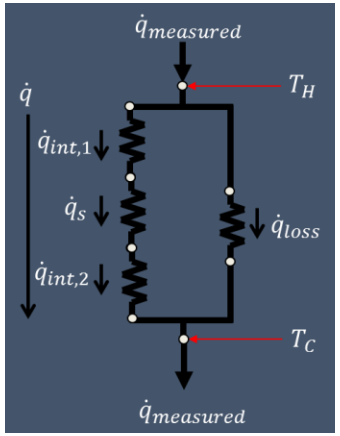


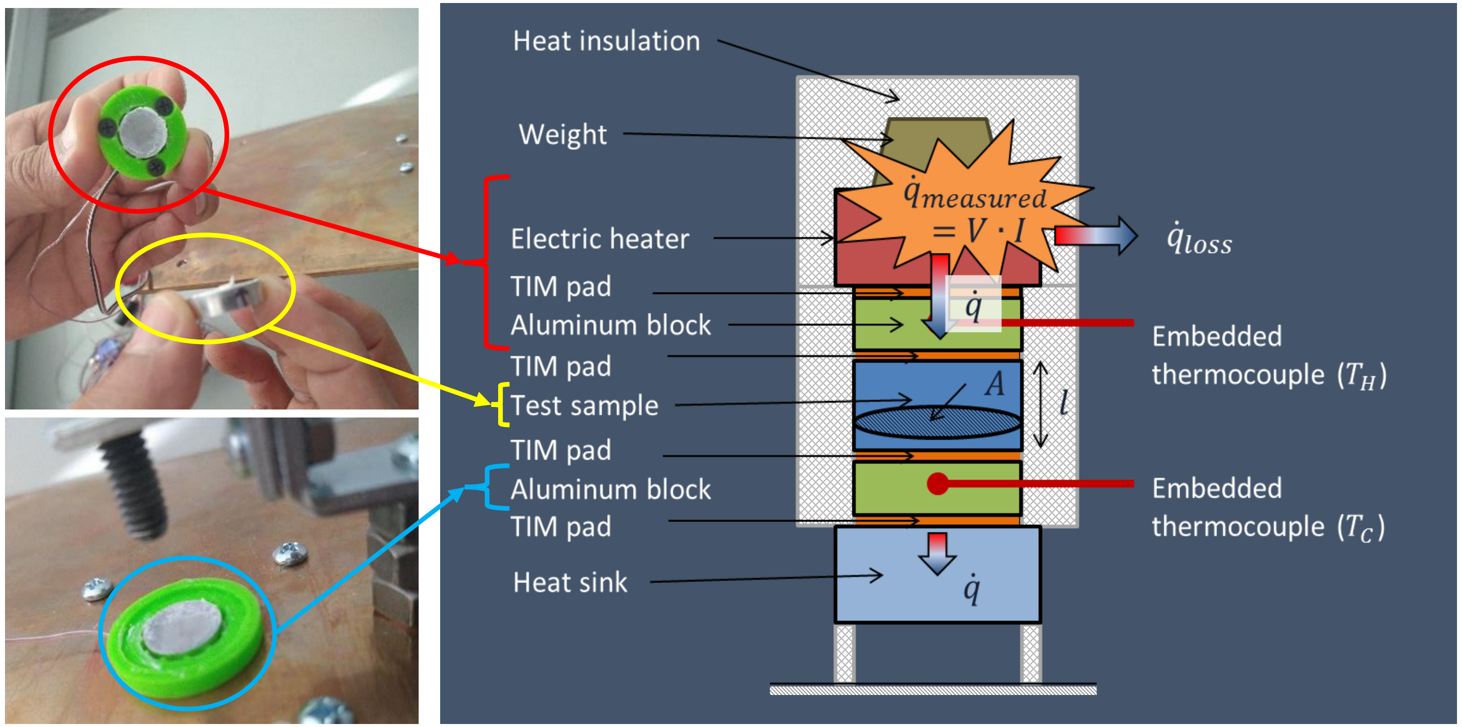
Steady-state heat equation (Fourier's law);

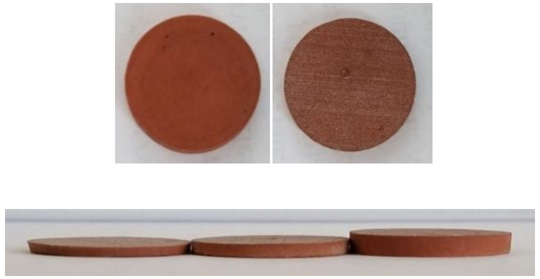
$$\dot{q} = \frac{\kappa \cdot A \cdot \Delta T}{l}$$

$$\dot{q} = \left(\frac{\kappa \cdot A}{l}\right) \cdot \Delta T$$

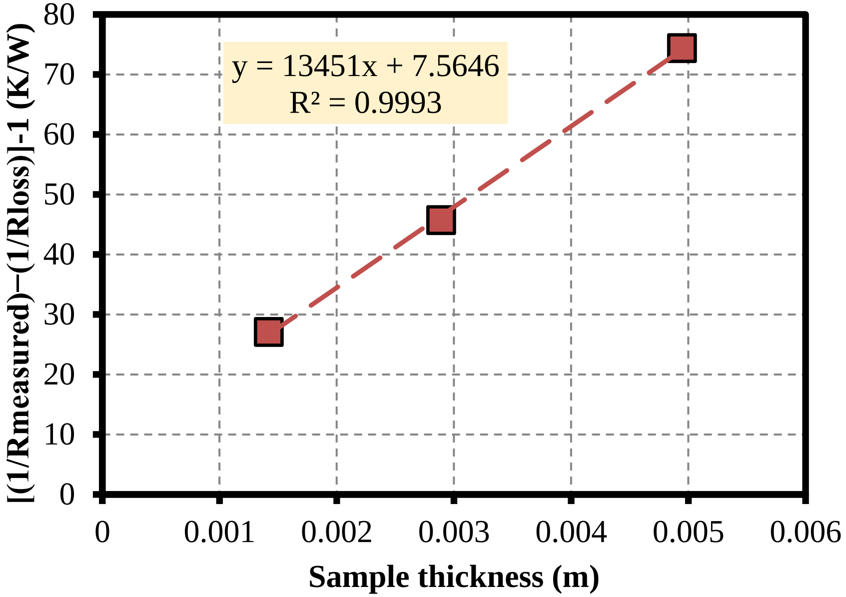
$$\dot{q} = \left(\frac{1}{R_s + R_{int}}\right) \cdot \Delta T \qquad \text{Where, } \Delta T = T_H - T_C$$







Source: Valeria Terentyeva-Holland, IES conference presentation Aug 2017

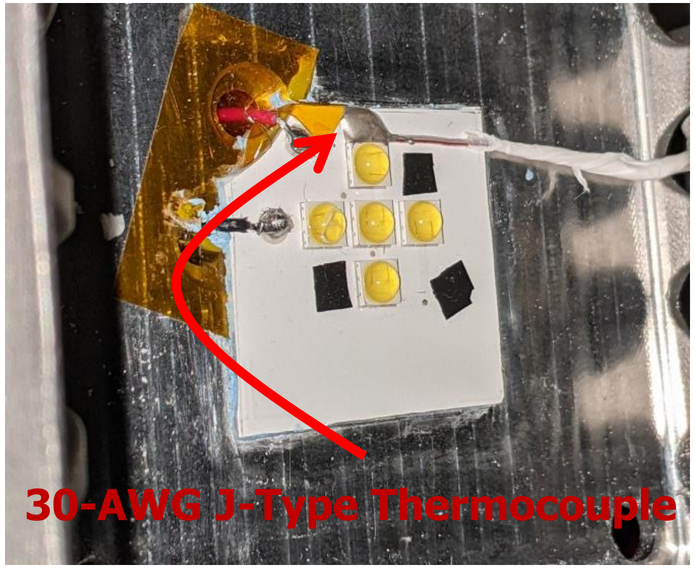


$$\left[\frac{1}{R_{measured}} - \frac{1}{R_{loss}}\right]^{-1} = \frac{1}{k \cdot A} \cdot l + R_{int}$$

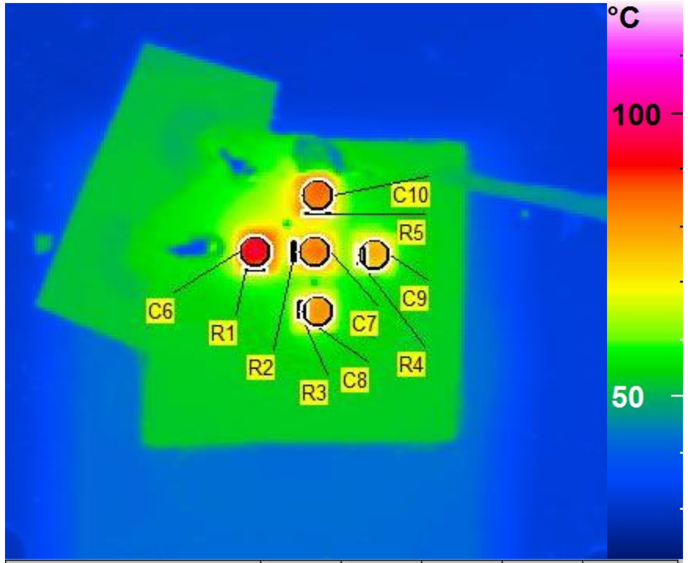
$$k = \frac{1}{m \cdot A}$$

Temperature measurements

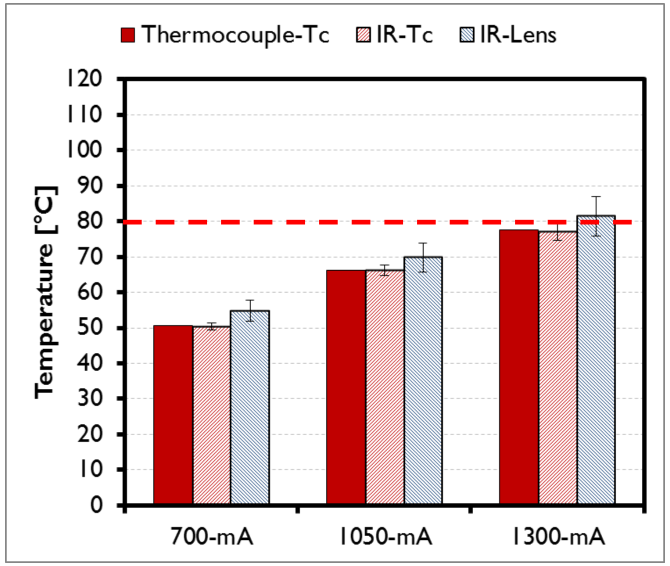
- Temperature sensor measurements



- Thermographic imaging measurements

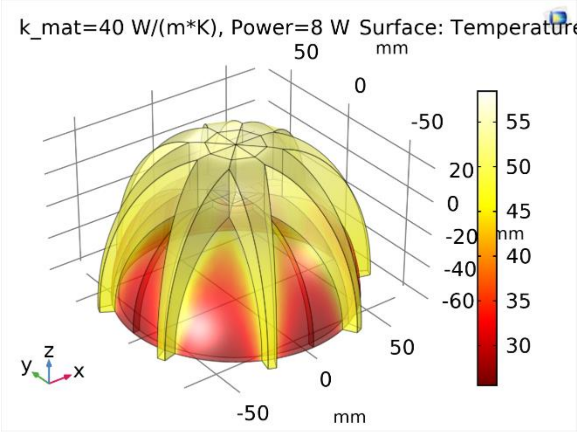


ROI	Avg	Min	Max	Sdv	Eps
R1 (156,132)-(162,132)	79.2 °C	77.7 °C	80.2 °C	0.81°C	0.95
R2 (171,123)-(172,129)	75.6 °C	72.7 °C	78.3 °C	1.71°C	0.95
R3 (173,142)-(175,147)	75.0 °C	73.0 °C	77.0 °C	1.27°C	0.95
R4 (192,125)-(194,130)	74.4 °C	71.4 °C	76.4 °C	1.21°C	0.95
R5 (175,114)-(183,114)	80.0 °C	75.5 °C	81.6 °C	1.88°C	0.95
C6 (154,121)-(164,131)	90.0 °C	83.2 °C	95.6 °C	3.33°C	0.97
C7 (173,121)-(183,131)	80.3 °C	76.0 °C	85.2 °C	2.41°C	0.97
C8 (174,140)-(184,150)	77.4 °C	69.9 °C	81.6 °C	2.85°C	0.97
C9 (192,122)-(202,132)	74.6 °C	69.2 °C	78.7 °C	2.13°C	0.97
C10 (174,103)-(184,113)	83.1 °C	77.4 °C	86.7 °C	1.96°C	0.97

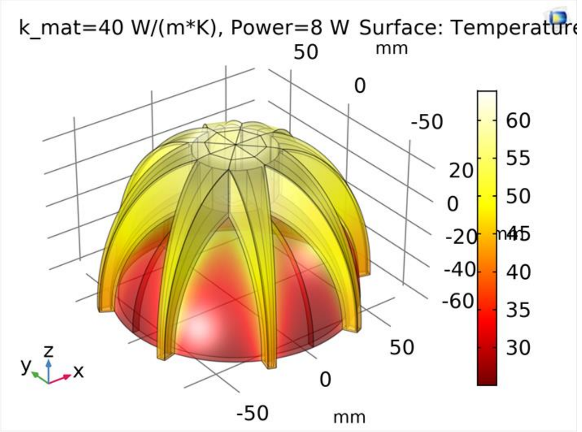


Thermal simulations of LED light engine design

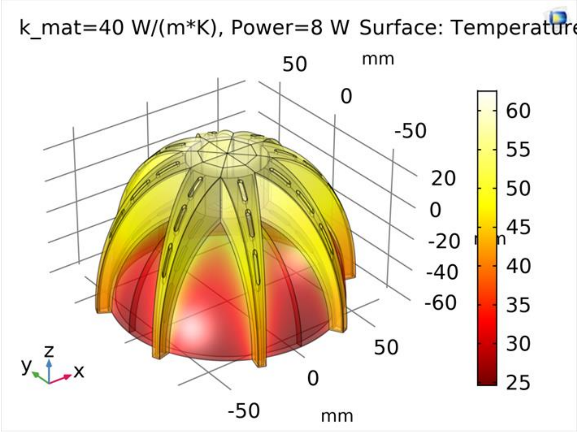
Solid



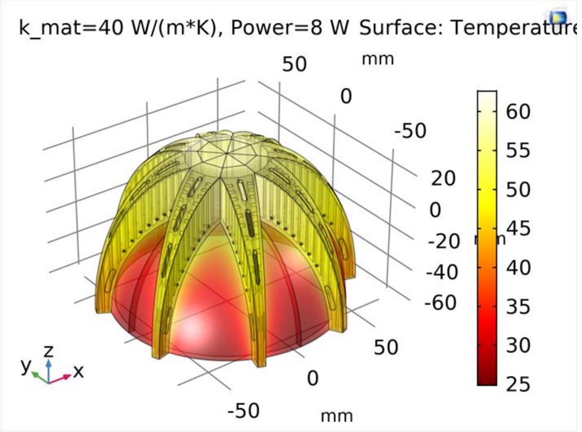
Hollow



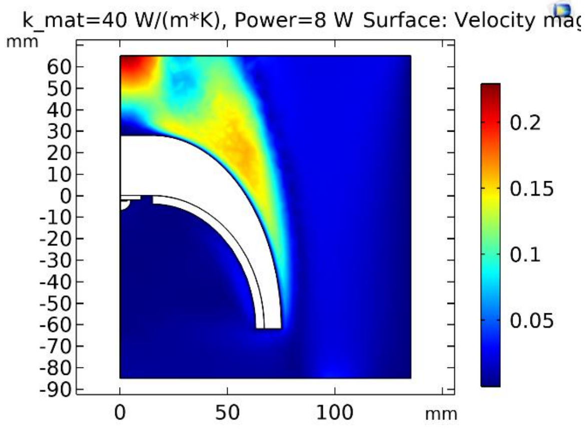
Vented Hollow



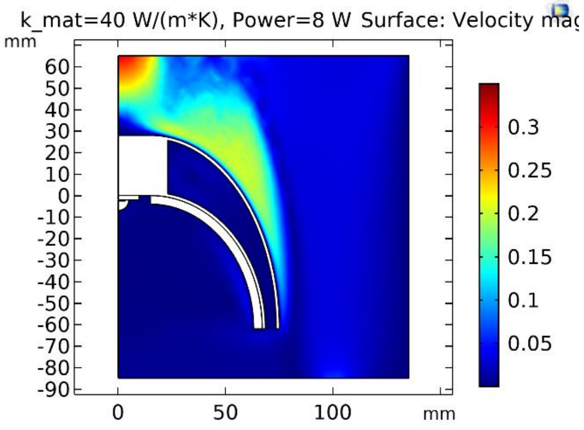
Vented hollow with internal columns



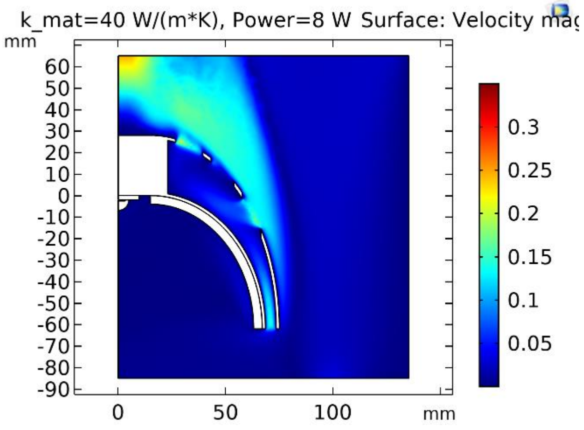
Solid



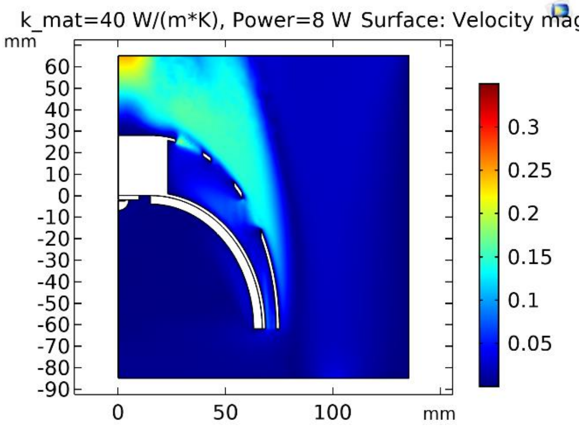
Hollow



Vented Hollow

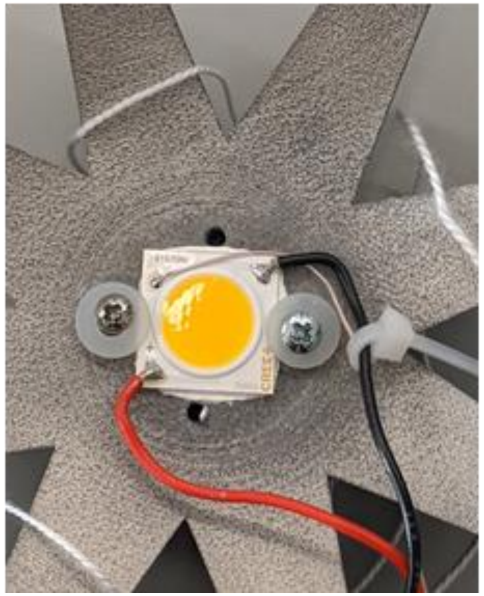


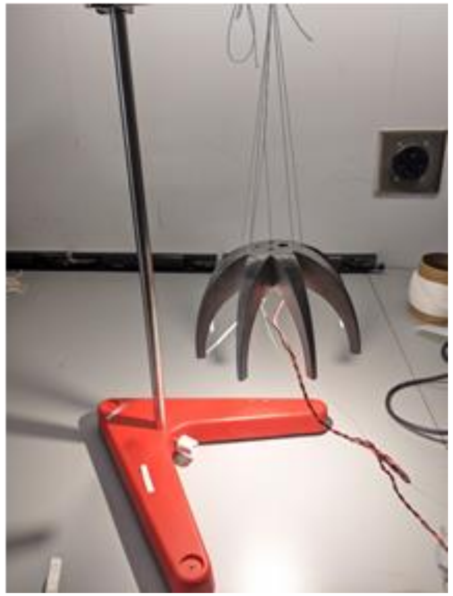
Vented hollow with internal columns

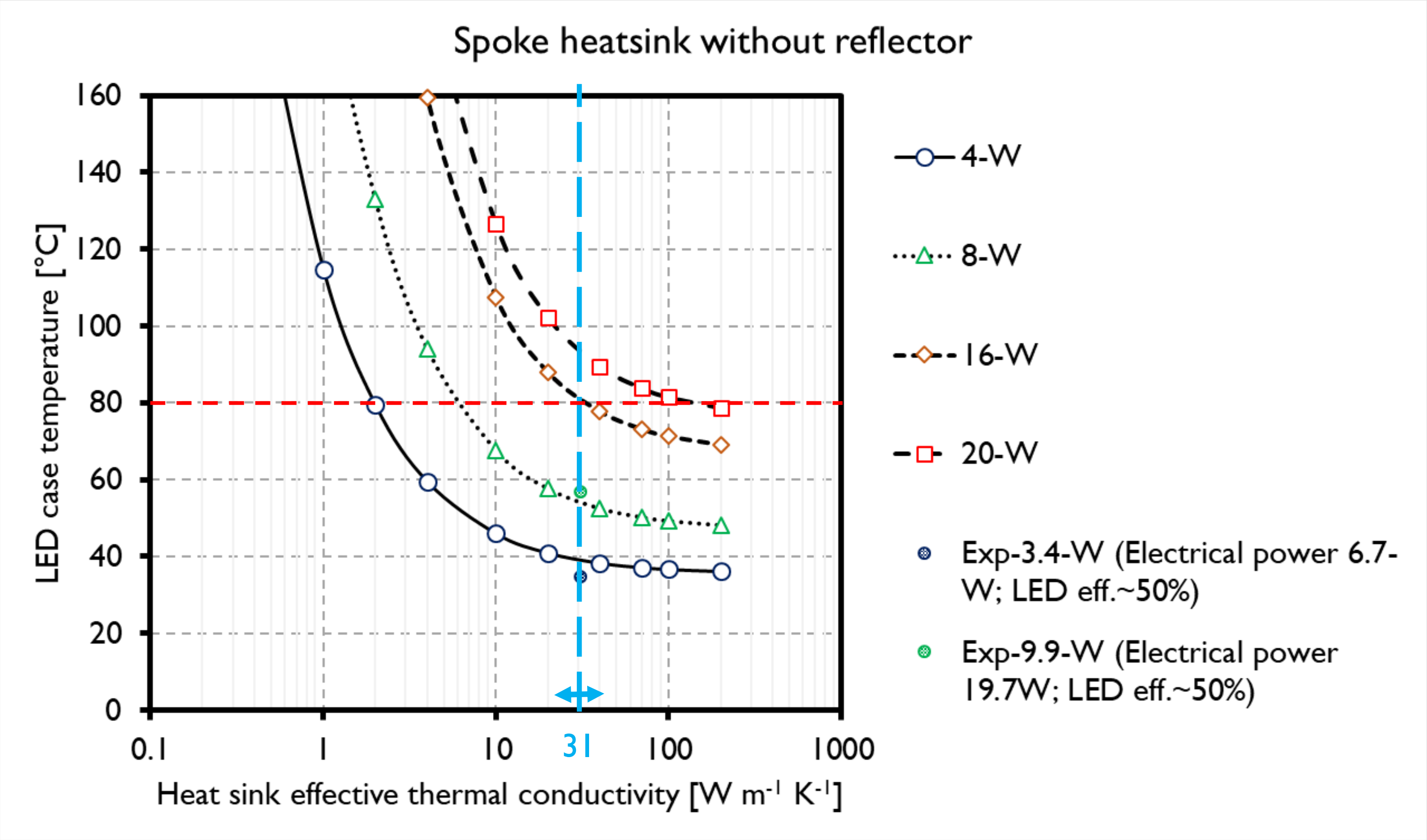


Thermal testing of samples and comparing with simulation results

	I_f [mA]	V_d [V]	P [W]	T_{case} [°C]
Solid Heatsink	200	33.3	6.7	34.9
	550	35.7	19.7	56.8
Hollow heatsink	200	33.3	6.7	35.5
	550	35.8	19.7	57.6







Summary: Prototype characterization

- Reflectance of reflector
  - AM reflector with Ni plating ~60%
  - AM reflector with specular reflective laminate ~90%

- Thermal conductivity of heat sink
  - Metal ~30-35 W m^{-1} K^{-1}
  - Polymer ~8-10 W m^{-1} K^{-1}
  - Tcase <80°C
  - Thermal simulation results match experiment

- Application efficacy ~120 lm/W
  - Increase # LEDs to increase efficacy
  - Investigate thermal interfaces and heat spreaders between LEDs and heat sink

Where Do We Go From Here?

Looking Forward: Where Can The Technology Improve?

- Cost
- Surface Finish of Printed Structures
- Materials
- System Level Considerations

Cost: Additive Mfg. Equipment/Processes

Main AM Cost Drivers

- Print time
- Size of printing bed (i.e. how many parts can be printed at one time)
- Post process tasks

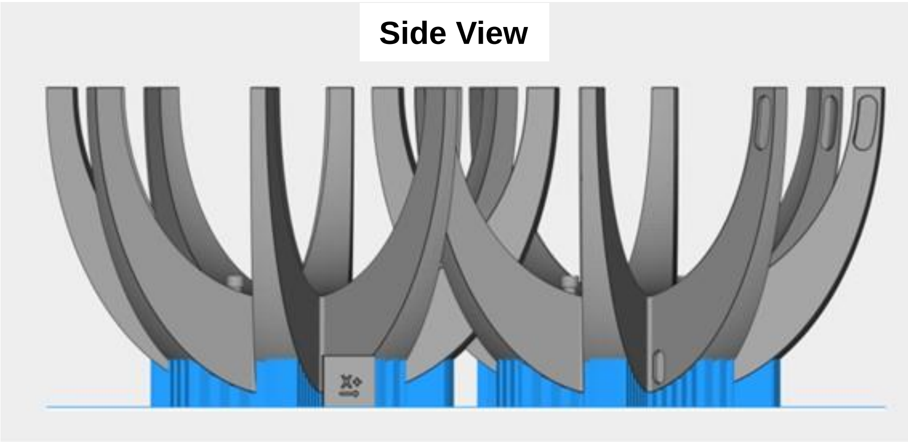
How can this be addressed?

- Faster AM processes
- Systems with larger beds and multiple lasers/print heads (emerging)
- Better “Net Shapes” (so minimal post processing)

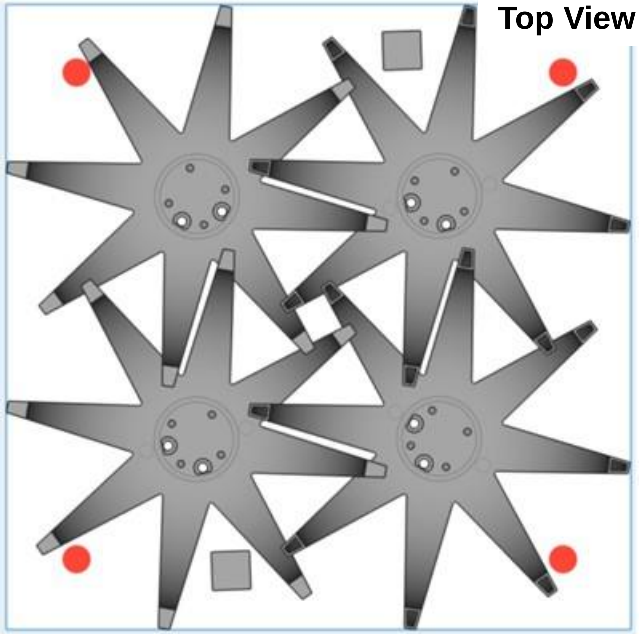
Key Gaps

1. High speed Additive Manufacturing processes for metals and polymers
2. Processes which can yield AM products closer to Net Shape

Nesting of Printed Heat Sinks



Top View



Surface Finish of Printed Materials

Metal Printed Surfaces

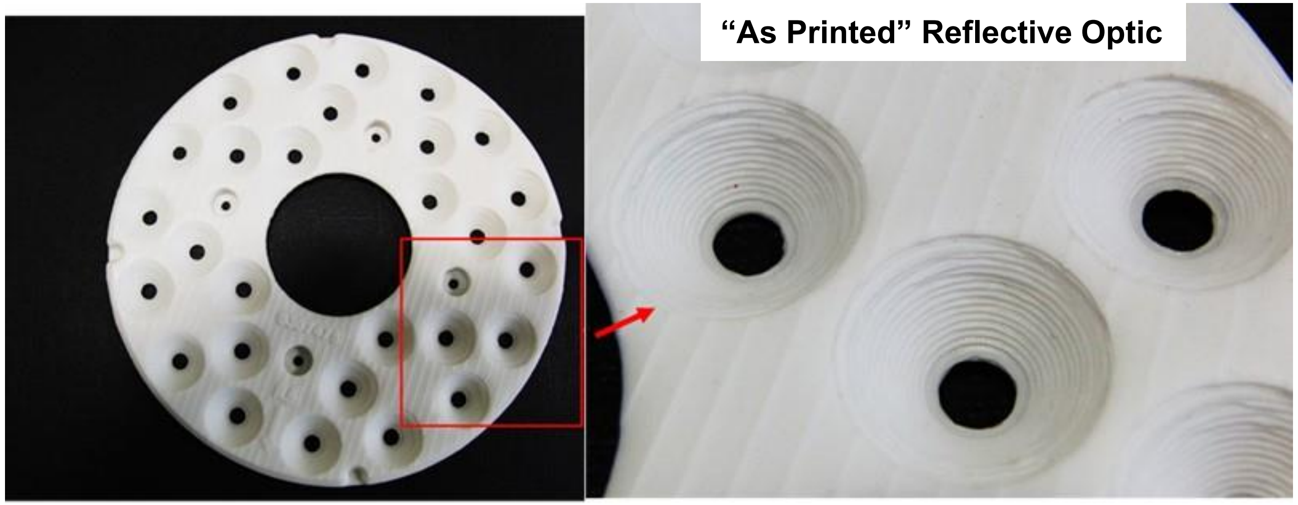
- Requires post processing for handling and application of printed electronics
- Process must be high volume, low cost (machining works but can be expensive)

Polymer Printed Surfaces

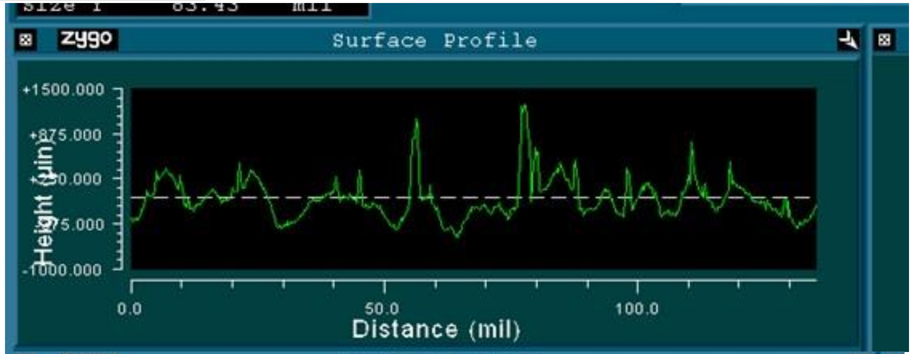
- Can use methods similar to metal but they are not as effective
- Optical components require some type of polishing to achieve properties similar to injection molding

Key Gaps

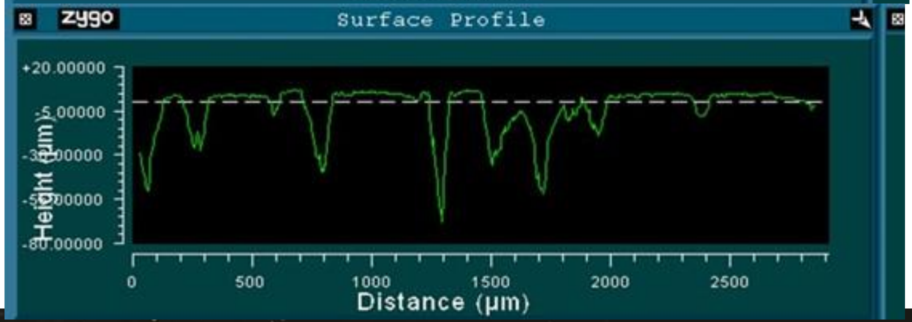
1. Better surface properties for net shape printing
2. Low cost, mass volume polishing methods for optical polymers



AM Metal Surface Profile, “As Printed”



AM Metal Surface Profile, Post Processed



Materials for Additive Manufacturing

Structural/Thermal

- Current AM metals seem sufficient for current application
- AM polymer materials with higher thermal conductivity ($>8\ Wm^{-1}K^{-1}$) difficult to find

Printed Electronics

- Existing material sets (dielectrics, conductors) are acceptable for LED circuits
- Curing time for some materials slows down process
- Printable, sensor materials (Temperature, piezo, photo, etc.)

Printed Optics

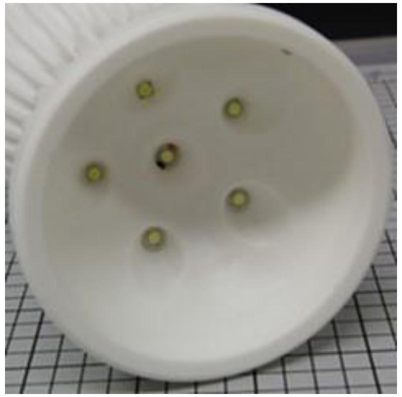
Reflective:

- Reflectance between 80%-90% (typical)
- Some yellowing in long term UV exposure
- Higher reflectivity materials emerging but being driven by non-lighting applications

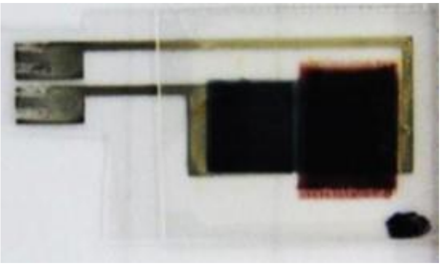
Refractive:

- Transmissivity > 93%
- UV degradation an issue

Printed Reflective Optic



Printed Photosensor



Key Gaps

1. Printable materials with improved optical properties and UV resistance
2. Polymer materials with higher thermal conductivities
3. UV and IR curing for electronic materials

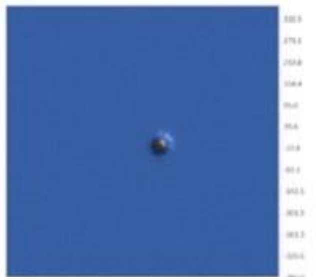
System Level Printing (Printed Optics, Print on Heatsink)

Printed Refractive Optics
- SLA Acrylic has minimal scattering and transmissivity >93%
- Scattering at filament interfaces
- Overall transmissivity <80% due to interfacial scattering
- Optical properties very process dependent
- High temperature capability (but Silicones emerging)

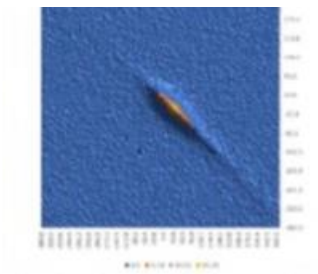
Printed Reflective Optics
- Reflectance between 80%-90% (typical)
- Higher reflectivity materials emerging but being driven by non-lighting applications
- High temperature capability (but Silicones emerging)

Printed Electronics on Heat Sink
- Lower LED temperatures with circuit printed directly on heat sink
- Easy to change designs with no tooling change
- Significant elimination/minimization of waste stream over traditional PCB fabrication methods
- Printing on 3D surfaces a potential enabler for improved performance

Minimal Scattering



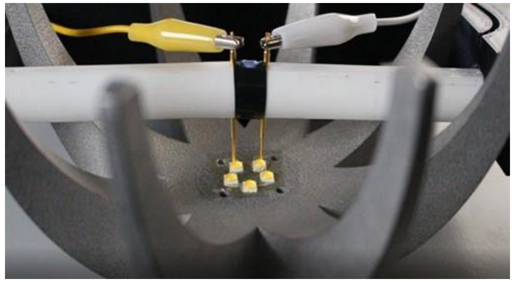
Interfacial Scattering



Setup #1

Setup# 15

Process Dependency of Printed Optics



Printed LED Circuit on AM Heat Sink

Key Gaps
1. Processes to minimize scattering
2. “Printable” materials with improved UV resistance

Questions?