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Thermal Simulations of an LED Lamp Using COMSOL Multiphysics

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LED Technology vs. traditional lighting technologies

- LEDs replace traditional light technologies incandescent, compact fluorescent and high intensity discharge light sources.

- The benefits of LEDs:
  - high luminous efficiency, up to 250 lm/W
  - long lifetime 25 000 – 50 000 hours
  - environmental friendly materials
  - fast response

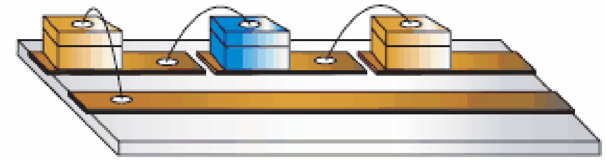
- Drawbacks of LEDs:
  - higher price
  - temperature control required

- Lifetime and light production of an LED light is affected by junction temperature of LED => proper thermal design and management is required

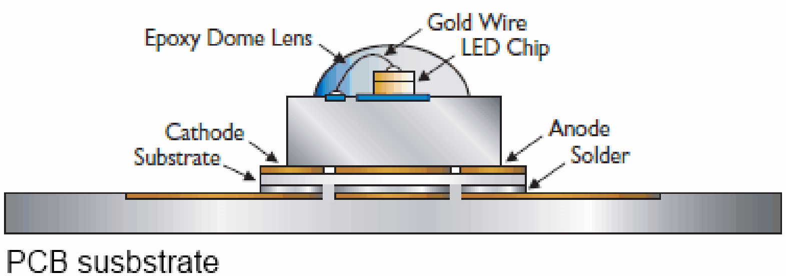
- Reliability of the LED driver

LED chip and packaging

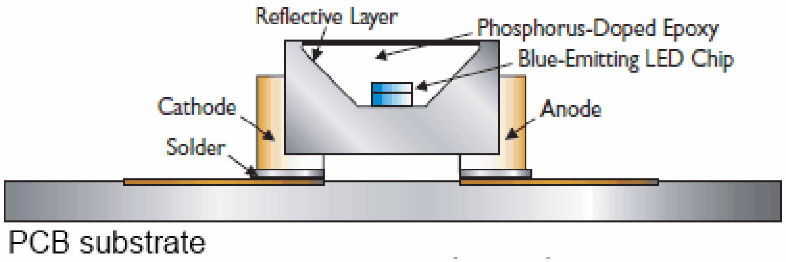
- HBR white LED is build using a blue light LED by adding a phosphorous layer above it
- Blue light LED is based on GaN.
- Typical thickness of structure composed of P-GaN and N-GaN layers is ≈ 5 um. This is the layer where light is generated.
- LED chip is mounted on a substrate and bonded. For HBR LED configuration is typically “face-up” or “vertical”.
- Multichip construction is typical for high brightness LED modules. LEDs are connected in series and in parallel.
- In this study the configuration of a LED is much simplified.



Standard Chip-On-Board structure



Thermally optimized structure



Blue light LED. Recessed die

Thermal resistance of a LED

- LED packages usually are either epoxy or silicone.
- Silicone is the most often used in the HBR LEDs.
- Most important thermal character of a LED package is the junction to case thermal resistance.
- Thermal resistance has decreased as packaging technologies have developed.

	typical Rj-c [°C/W]
1960's	250
1990's	6-12
2000's	< 5

Junction to case thermal resistance over the past decades.

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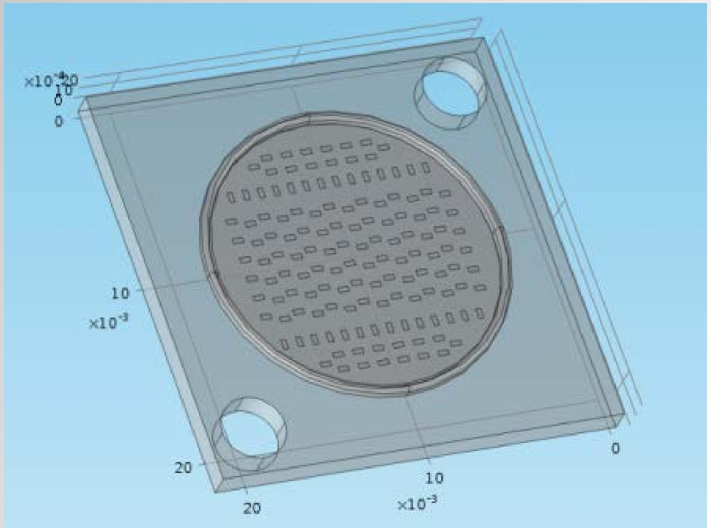
CAD model for the HBR LED module



- Multichip using 140 LEDs.
- Size 20 mm x 20 mm, LEDs in a circle of d=16 mm.
- Aluminum heatsink, silicone capsulation.
- Power ≈14 W (350 mA, 40 V).
- Luminous flux ≈1100 lumens (lm), 78 lm/W, radiation angle 120°.

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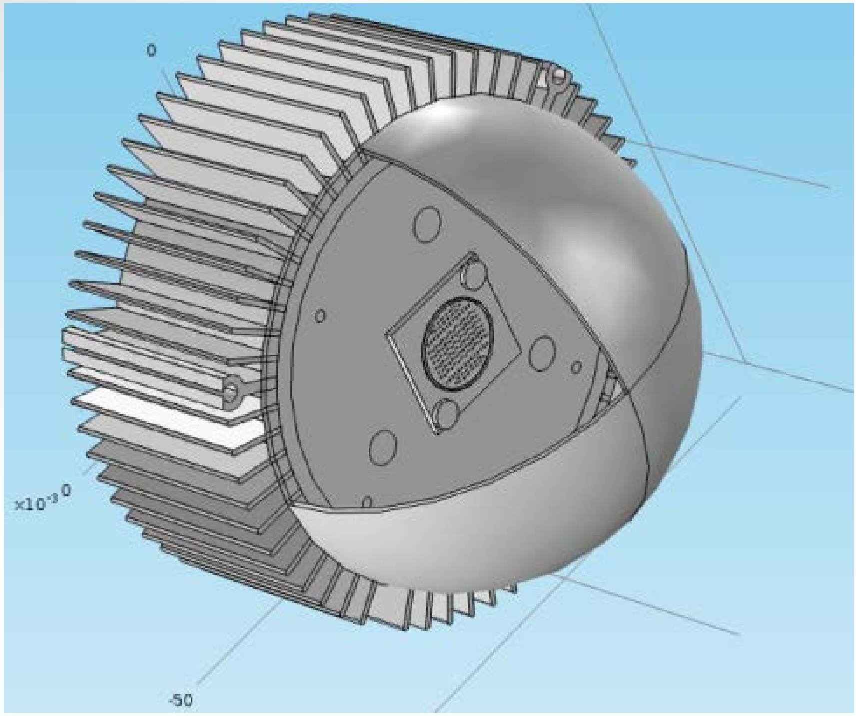
CAD model for the LED lamp

- A LED module, an aluminum heatsink and a plastic bulb.
- A down-light on ceilings, a spot light etc.
- The bulb sealing is not air tight.
- Thermal interface material between the LED module and the heatsink.
- A separate LED driver.



Multiphysics thermal simulation for the LED lamp

- Typical for LEDs:

  - relative low temperatures
  - usually external natural heat convection
  - air flow over a heatsink is almost always laminar, non-turbulent

- Joule Heating physics selected and included the following models:

  - Heat Transfer in Solids
  - Heat Transfer in Fluids
  - Convective Cooling
  - Surface to Ambient Radiation
  - Surface to Surface Radiation
  - Heat Source
  - Thin Thermally Resistive Layer

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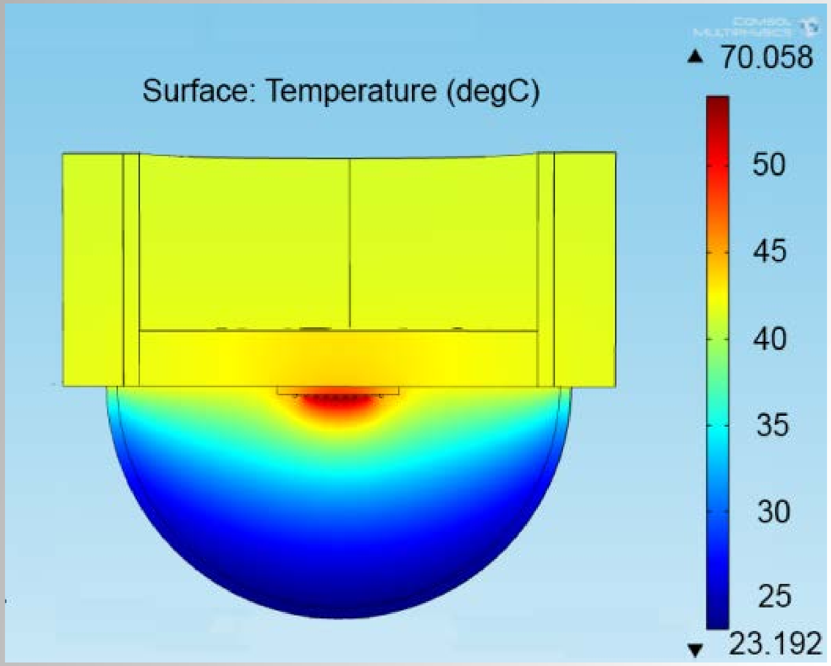
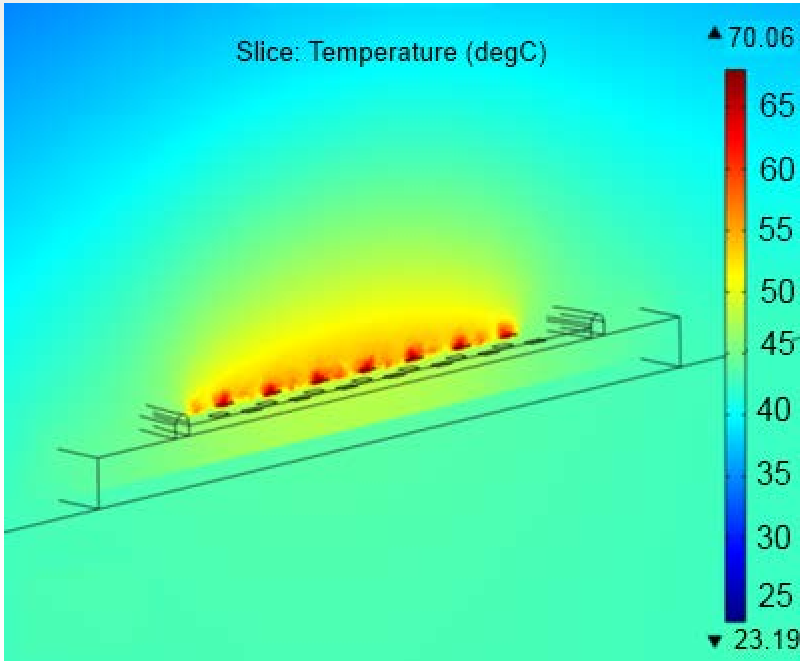
Simulated temperatures and thermal resistances

- Symmetry used (one half).
- Solution in stationary condition.
- Surface and intersection temperatures.

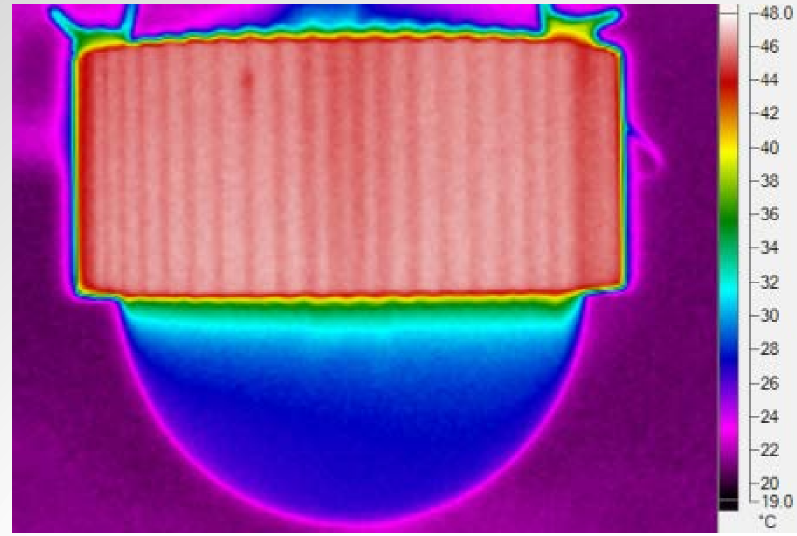


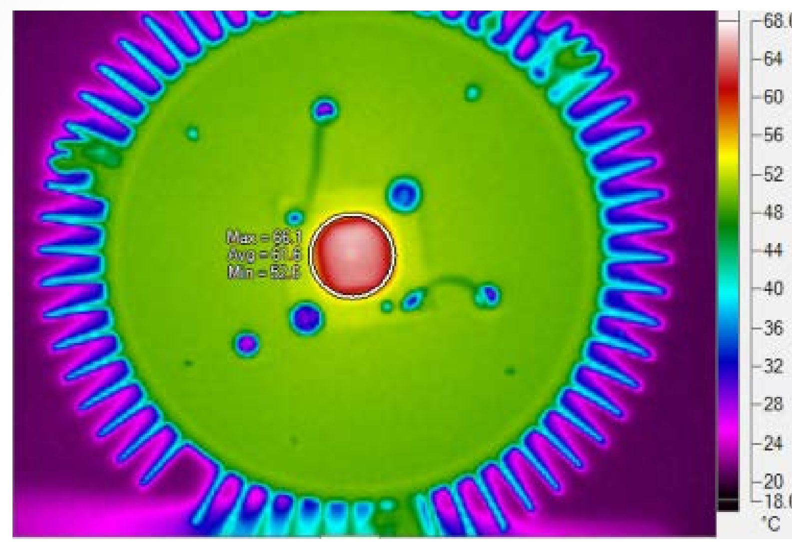


IR images of the LED lamp

- 14.46 W power dissipation.
- Surface temperature as seen by an IR-camera (ambient 21 °C).

Domain	Surface Temperature [°C]
Heatsink	40-43
LEDs	66 (max), 62 (avg.)
LED module	49





Simulated average temperatures and thermal resistances in stationary thermal condition

Domain	Avg. Temperature [°C]
Ambient	21.0
Heatsink	41.8
LED module	46.0
LEDs	64.4
LED junction	86.5 [1]

1) Temperature (V,I) data from the manufacturer.

Thermal Resistance	R_{th} [°C/W]
LED chip to module $R_{th,\ j\text{-}m}$	3.55
LED module to heatsink $R_{th,m\text{-}h}$	0.36
Heatsink to ambient $R_{th,h\text{-}a}$	2.30
LED junction to ambient $R_{th,j\text{-}a}$	5.66

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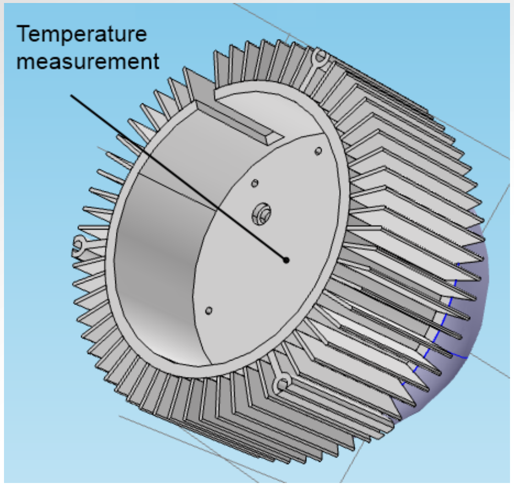
Time dependent simulations

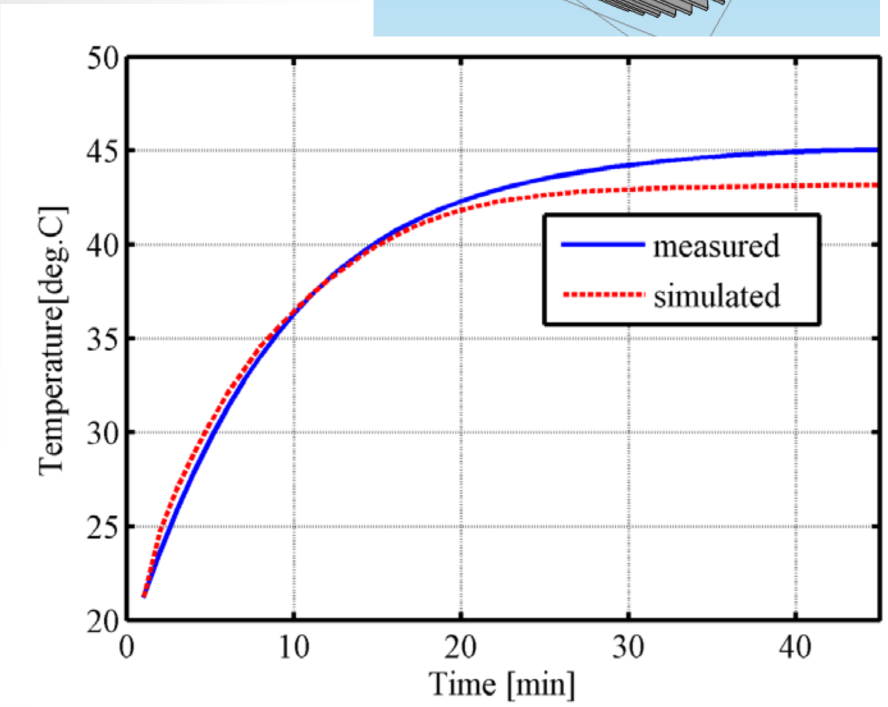


- Time dependent behavior is determined by the thermal resistance and heat capacity of the main heat transfer path.

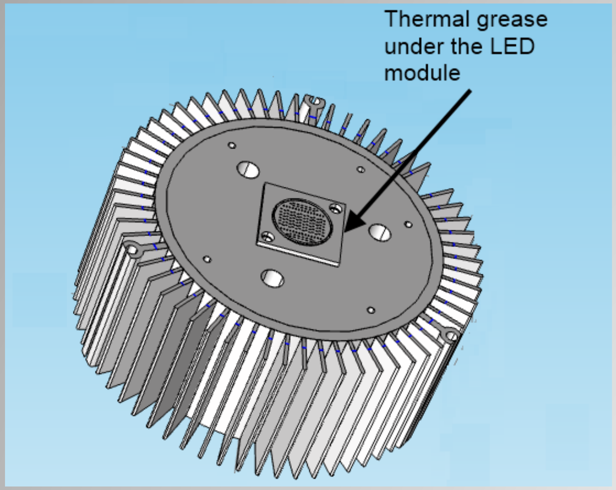
$$\Delta T(t) = R_{th}(1 - \exp(-t/R_{th}C_h) \cdot P$$

ΔT temperature difference [°C]
t time [s]
R_{th} thermal resistance [°C/W]
C_h heat capacity [J/°C]
P heat flow [W]

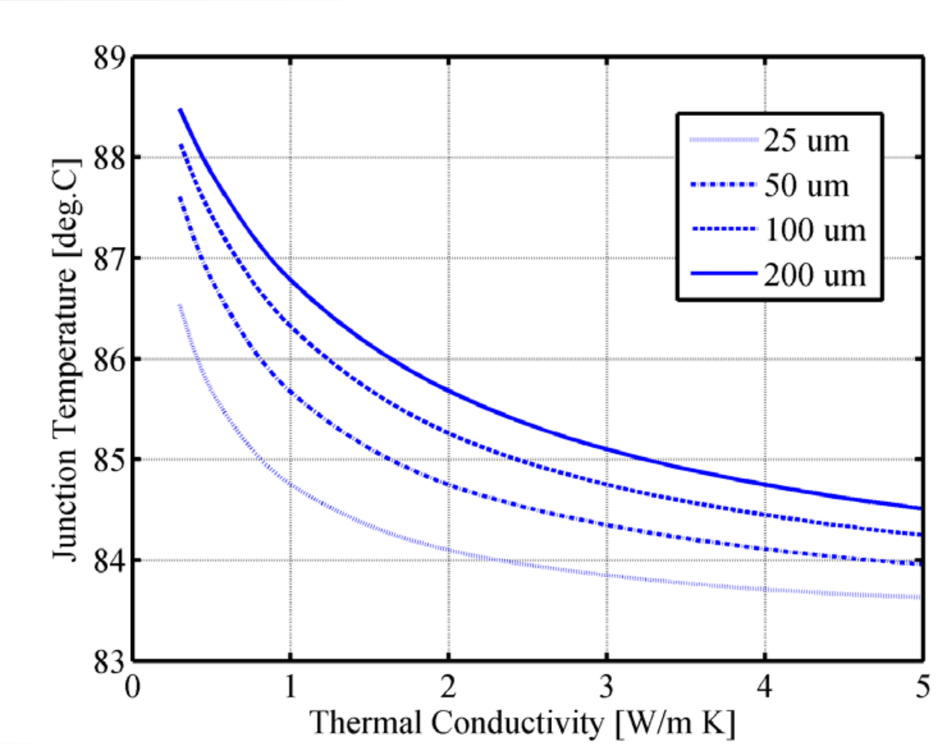
- Temperature measurements with type K thermocouples.



Thermal grease layer - simulations



- Thermal interface material between the LED module and the heatsink.
- Usually silicone compounds.



- Thin thermally resistive layer model.
- Simulations for different thickness and thermal conductivity.
- Obvious conclusion:
  The grease layer as thin as possible.

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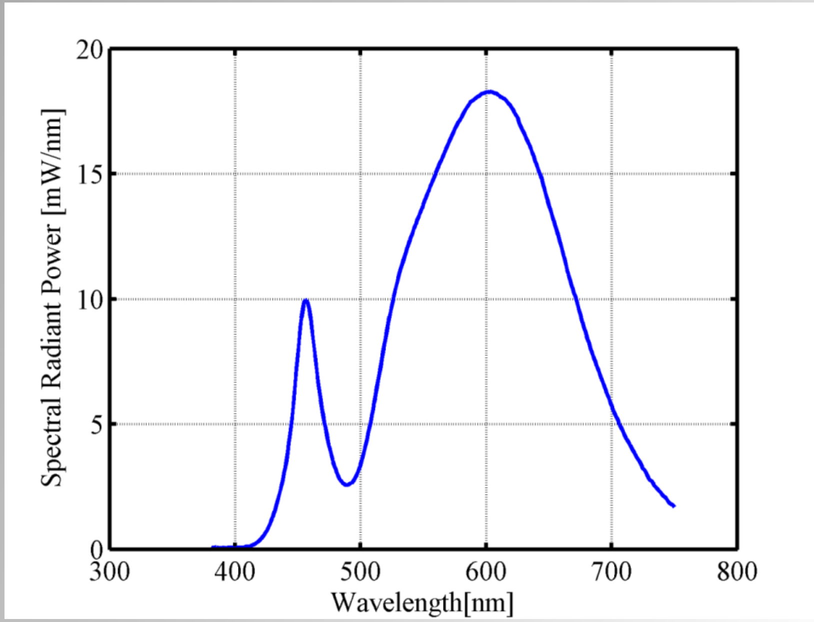
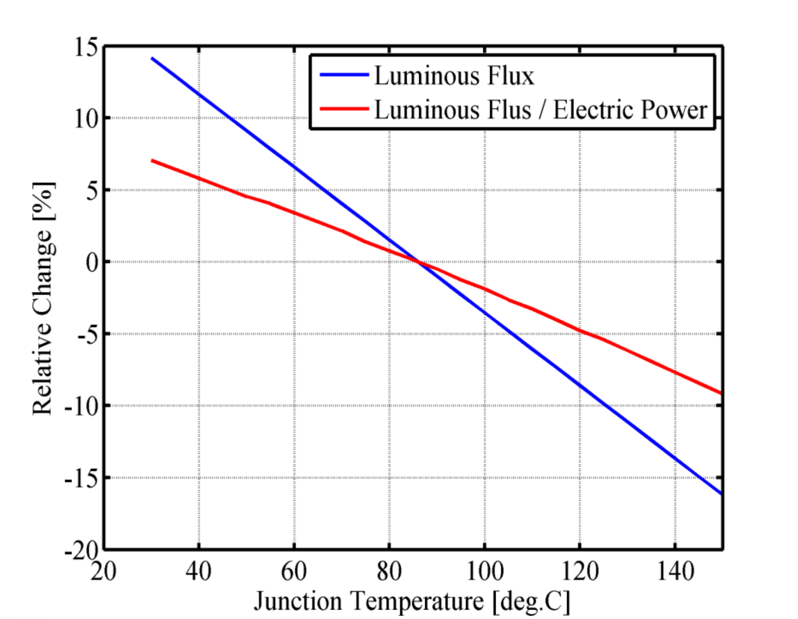
Photometric measurements of the LED lamp



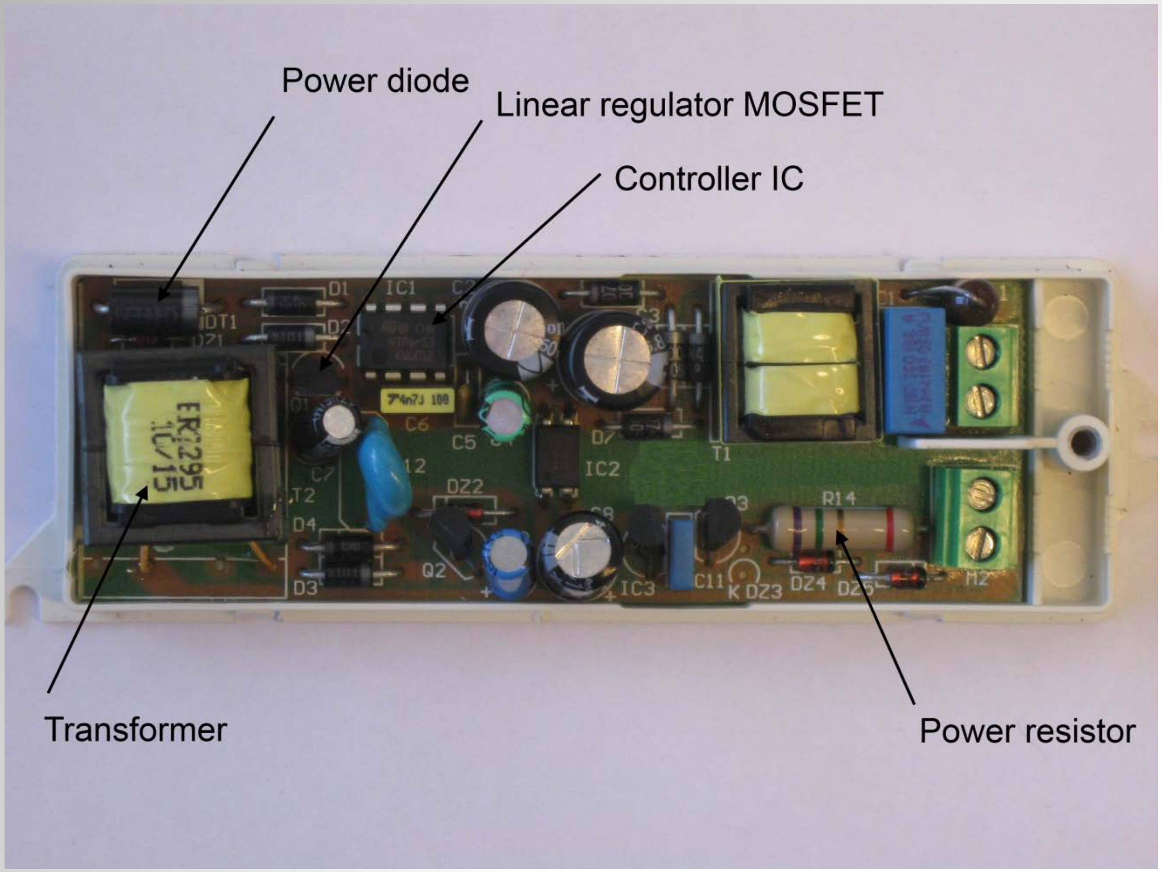


Configuration	[lm]	[lm/W]	[%] [1]
without the bulb	1072	72.1	22.7
with the bulb	986	66.3	21.8

1) Electro-optical efficiency.

- Luminous flux decreases when the junction temperature increases.
- Power sink increases slightly when temperature decreases.

LED driver



- Offline, isolated LED driver.
- Input 100-240 VAC, 50/60 Hz.
- Constant current output 350 mA, max 48 V.
- Efficiency ≈ 80 %, power factor ≈ 0.6.

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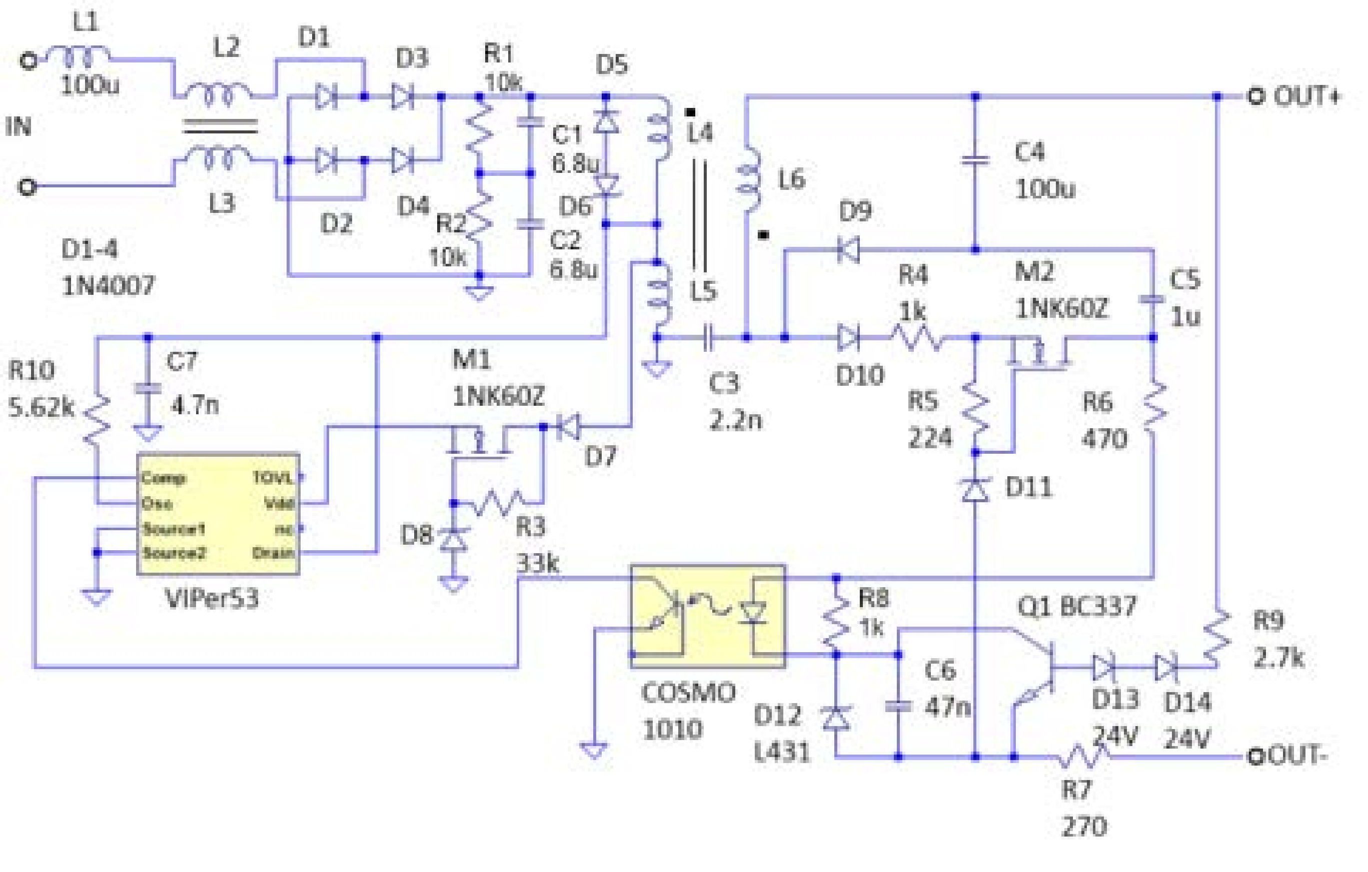
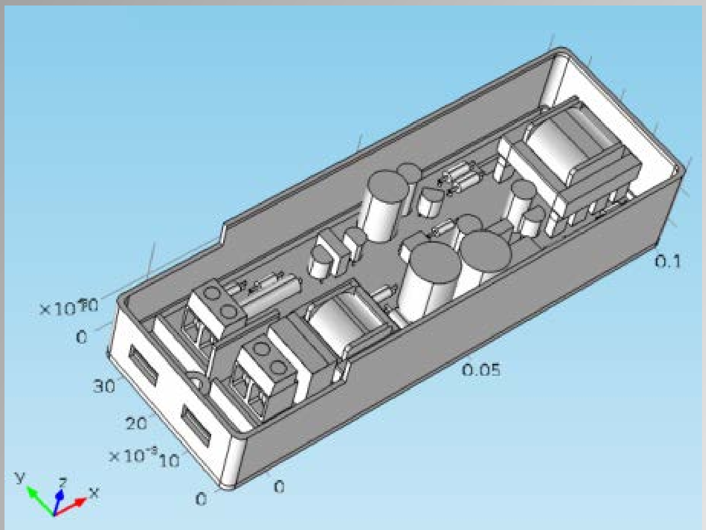
LED driver

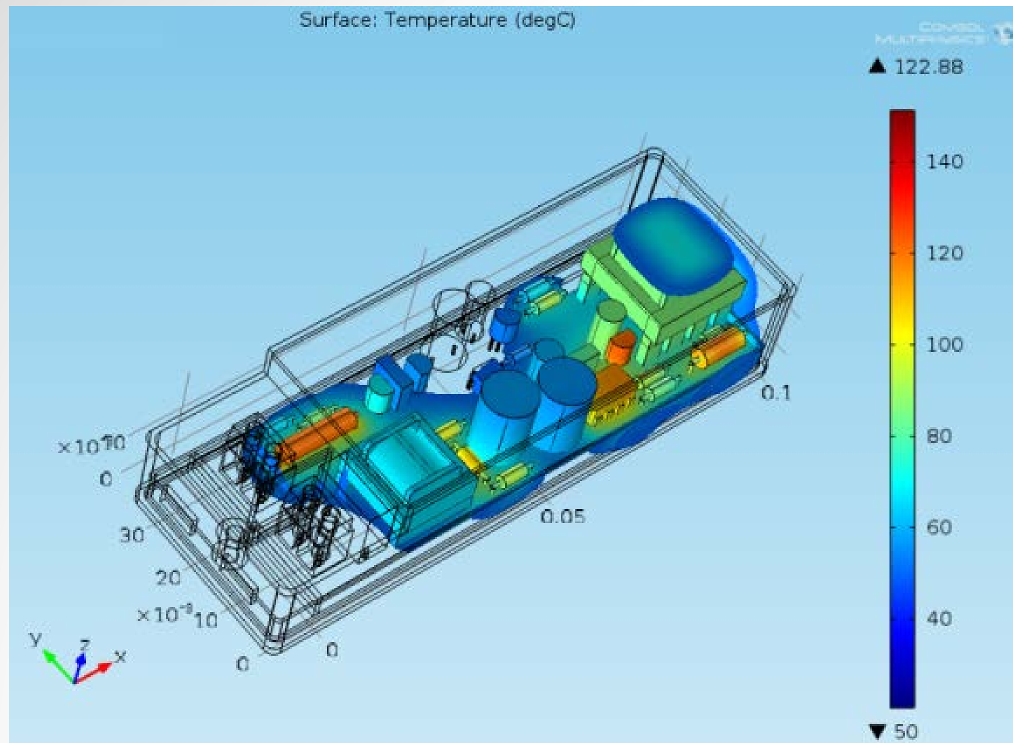


- Switching (50 kHz) power supply, Flyback topology.
- Main sources of heat: controller IC, linear regulator M1, power resistor R7 and diode D5.

Thermal simulations of the LED driver



- Heat dissipation are resolved by using a circuit simulator and measurements.
- Equivalent heat sources added for the main components.



- Thermal simulations for case the enclosure is partly opened.
- Natural external convection.
- "Thin Thermally Conducting Layer" model for copper side of the PCB.

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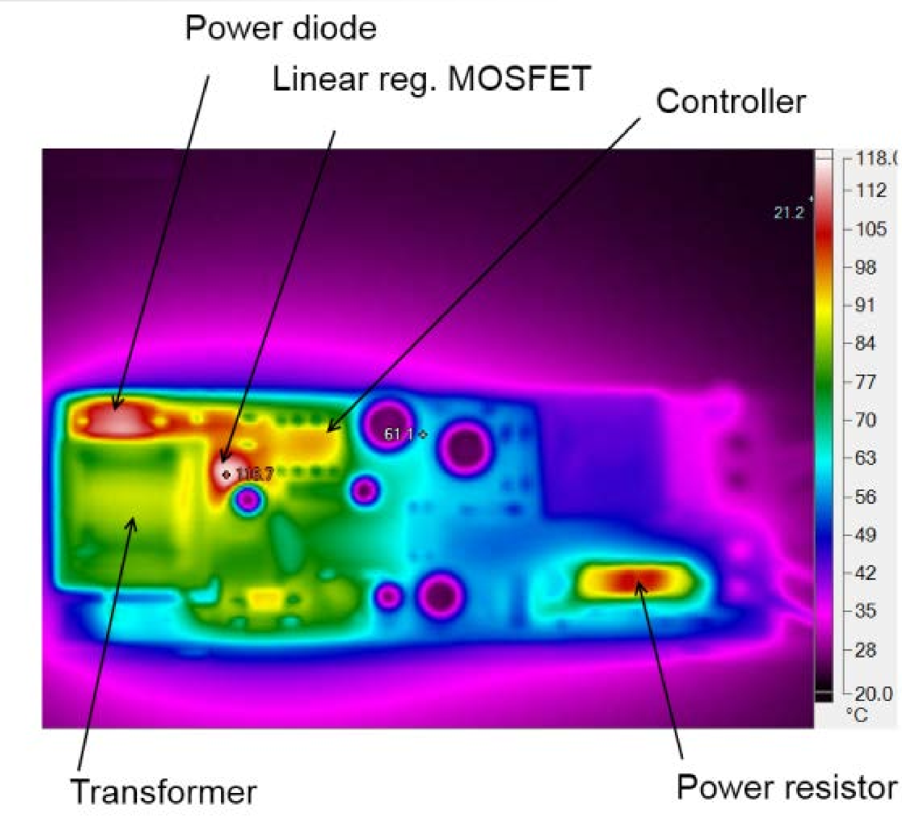
IR images of the LED driver

Component	Surface Temperature [°C]
Controller IC	95
Regulator MOSFET	117
Power diode	111
Power resistor	105
Transformer	86



Conclusions

- Thermal simulations for an experimental LED lamp and a commercial LED driver.
- Stationary condition and time dependent simulation in external natural heat convection have been done.
- Thermal resistances were resolved.
- Junction temperatures of the LEDs were resolved.
- The effect of thermal interface material was studied.
- Simulations validation using thermocouple measurements and IR-imaging.
- Photometric measurements resulted in luminous flux and spectrum.
- The LED driver was modeled and simulated.
- The main conclusions:

  - the LEDs are well cooled and have efficient light generation.

  - several components of the LED driver operate at too high temperature.

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- References:

M.Maaspuro and A.Tuominen, “Energy Efficiency and Thermal Simulations of a Retrofit LED Light Bulb”, LED Professional Magazine Review, LpR 33, August/September 2012.

M.Maaspuro and A.Tuominen,“Thermal Analysis of LED Spot Lighting Device Operating in External Natural or Forced Convection”, Microelectronics Reliability Magazine (in print).