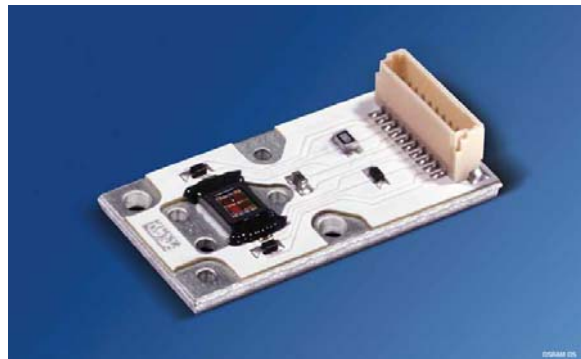


Thermal Management of OSTAR[®] Projection Light Source

Application Note

Abstract

This application note provides an introduction to the thermal fundamentals of the compact LED high power light source OSTAR[®] Projection from OSRAM-OS. In addition, the general handling of the new light source will be briefly covered, and the requirements for the necessary heat dissipation and cooling will be described.



Introduction

The recently introduced high-power LED OSTAR[®] Projection rings in a new era for compact semiconductor light sources.

With a luminous flux of more than 200 lumens at RGB-white, it pushes the standard to a new record level regarding brightness, and surpasses customary LED light sources by great lengths.

Based on semiconductor chips of the newest thin film technology with pure surface emission, it exhibits exemplary Lambertian radiation characteristics and offers uniform, angle-independent luminance within the smallest space.

Available as a single color, RRBB or RRGB module with a small size of 30 x 10 mm, the OSTAR[®] Projection offers an extreme measure of design freedom and flexibility and permits advancement into new application areas such as general lighting, medical technology, projection or automotive technology.

The OSTAR[®] Projection is designed for a power consumption of 10 W or more. As with all semiconductor components, the function of the LED is influenced by temperature.

In order to achieve reliability and optimal performance of the light source, appropriate thermal management is imperative.

Handling of the OSTAR[®] Projection Light Source

In order to protect the semiconductor chip from environmental influences such as moisture, the OSTAR[®] Projection is equipped with a clear silicone encapsulant which additionally provides a positive influence on the reliability and lifetime.

Moreover, the silicone encapsulant permits operation at a higher junction temperature compared to that of standard LEDs.

Due to the elastic properties of the encapsulant, however, mechanical stress to the silicone should be minimized or avoided as much as possible during assembling of the LED (see Application Note "Handling of Silicone Resin LEDs"). Accordingly, care must be taken with the black Globe-Top encapsulant of the connecting pins.

Exertion of pressure on the Globe-Top connector can lead to a spontaneous failure of the light source.

To prevent damage to or puncturing of the encapsulant, the use of all types of sharp objects should generally be avoided, since this can damage the component.

In addition, it should be assured that sufficient cooling is available when the compact light source is placed into operation.

Continual operation without cooling, even at low current, can lead to overheating, damage or failure of the module.

Construction of the OSTAR® Projection Light Source

During design of the OSTAR® Projection light source, special attention was given to the thermal optimization of the module.

The module core consists of four highly efficient semiconductor chips soldered to a ceramic base.

For optimal heat dissipation, the ceramic is directly mounted to the aluminum surface of the isolated metal core PCB (IMS-PCB). This MC-PCB acts as a heat spreader, providing a large surface area for efficient thermal contact to the system heat sink.



Figure 1: Construction of the OSTAR® Projection

The power dissipation P_D at the active layer of the semiconductor chip is conducted by the ceramic and from there, distributed to the aluminum board. The heat is further transferred from the aluminum board by means of direct contact with the heat sink. Heat transfer occurs from the free surfaces of the heat sink to the environment by means of radiation and convection.

In addition, an NTC resistor is mounted on the OSTAR® Board which permits implementation of a feedback loop for temperature monitoring in the driver circuitry.

The NTC temperature can provide a good approximation of the average temperature on the underside of the board.

Basic Relationships

Operation of LEDs is basically limited by several factors which on the one hand are dependent on the material and on the other are contingent on the technology. An important parameter of practical interest is the temperature of the active semiconductor layer or junction layer (T_{junction}), since this influences the function and lifetime of the component.

In order to prevent damage to the device during operation, the manufacturer recommended maximum junction temperature should not be exceeded.

The goal of thermal management is to keep the junction temperature for a given application as low as possible.

The first line of support for the development of thermal management is the thermal resistance value (R_{th}).

Analogous to Ohm's Law, this is defined by the following formula:

$$U = I \cdot R \leftrightarrow \Delta T = P_D \cdot R_{th} \quad (1)$$

For an OSTAR® Projection light source with a heat sink, the thermal resistance $R_{th,JA}$ can be defined as follows:

$$R_{th, \text{Junction-Ambient}} = \frac{\Delta T_{\text{Junction-Ambient}}}{P_D} \quad (2)$$

where:

$$\Delta T [K] = T_{J(\text{unction})} - T_{A(\text{mbient})}$$

$$P_D [W] = U_f \cdot I_f = \text{power dissipation}$$

$$U_f [V] = \text{forward voltage}$$

$$I_f [A] = \text{forward current}$$

The relevant junction temperature is then obtained by:

$$T_J = R_{th,JA} \cdot P_D + T_A \quad (3)$$

The thermal resistance $R_{th,JA}$ in turn is represented by the sum of the individual resistances along the thermal path from the active semiconductor layer to the outside ambient temperature.

For the OSTAR[®] Projection, the total resistance can be divided into an internal and an external (application specific) thermal resistance.

$$R_{th,JA} = R_{th,JB} + R_{th,BA} \quad (4)$$

$R_{th, J(unction)-B(oard)}$

$R_{th, B(oard)-A(mbient)}$

The internal thermal resistance $R_{th,JB}$ is defined by the physical construction of the OSTAR[®] Projection LED.

It describes the thermal characteristics of the LED starting from the junction layers of the four highly efficient semiconductor chips to the ceramic and finally to the underside of the aluminum base plate.

The values for $R_{th,JB}$ can be found in the corresponding data sheets for the OSTAR[®] Projection LED.

The outside thermal resistance $R_{th,BA}$ defines the connection of the OSTAR[®] Projection to a heat sink and the thermal properties of the application specific cooling. It is strongly influenced by various factors such as component layout, material/properties of the LED connection, cooling design, fans etc.

The issue is simplified by the following resistance model (Figure 2) which makes use of analogies to electronics:

- The heat dissipation P_D close to the chip surface is simulated by a current source.
- The "resistor network" consists of a parallel circuit and a series circuit to the ambient temperature.
- The ambient temperature is represented by a voltage source.

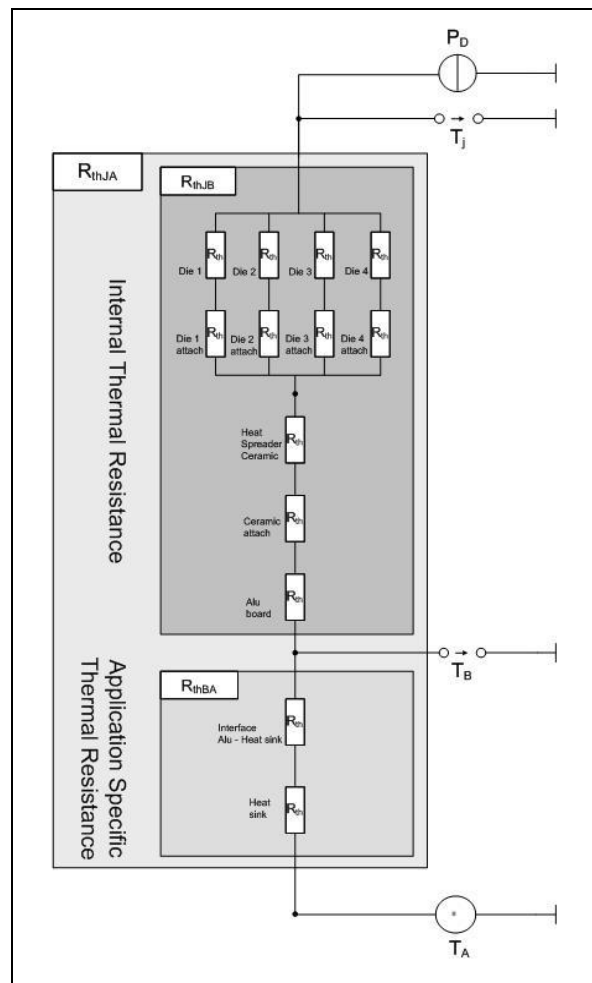


Figure 2: Static equivalent circuit

In general, the thermal management of the OSTAR[®] Projection light source can be divided into two categories: internal and external thermal management.

The internal management addresses the thermal resistance from the junction layer to the carrier board while the external thermal management addresses thermal resistance from the connection of the board to the environment.

Because of the predefined values for the internal resistance, the external management plays a significant role which includes the selection of an application specific cooling method, the design of the cooling element, the material selection as well as the mounting process.

Transient Thermal Resistance Z_{th}^* for Pulsed Operation Conditions

While the thermal characteristics for stationary states can be described by the thermal resistance R_{th} , dynamic, pulsed processes additionally require that the thermal capacitance of all components be taken into account.

Due to the complex interrelations and transient behavior of pulsed systems, one usually considers the thermal state at the end of a pulse in order to obtain an impression of the maximal change in temperature.

To calculate the maximum junction layer temperature, a first approximation can be obtained by:

$$T_{Junction} = T_{Board, Bottom} + Z_{th}^* \cdot P_D$$

where

$$P_D [W] = U_f \cdot I_f = \text{power dissipation}$$

$$U_f [V] = \text{forward voltage}$$

$$I_f [A] = \text{forward current}$$

Z_{th}^* describes the transient thermal resistance dependent on the repetition rate and the duty cycle.

If Z_{th}^* is multiplied by the maximum power dissipation during the pulse, an upper estimate for the junction temperature can be obtained.

Figures 3 to 5 show the characteristics of Z_{th}^* for the OSTAR[®] Projection LED module for operation with one, two or four chips, in relation to the duty cycle D ($D = t_p/T$). The various curves in the diagram represent different repetition rates.

For a more precise, detailed view of the thermal behavior of the device during and between the pulses, one can resort to an electro-thermal simulation of the corresponding equivalent thermal circuit diagram. This allows the time dependent temperature behavior to be precisely modeled and visualized.

As can be seen in Figures 3 to 5, the transient thermal resistance Z_{th}^* decreases at lower duty cycles and at higher frequencies.

When designing the thermal management, it should be determined whether an improved performance level can be achieved by increasing the switching frequency or decreasing the duty cycle while maintaining the system parameters.

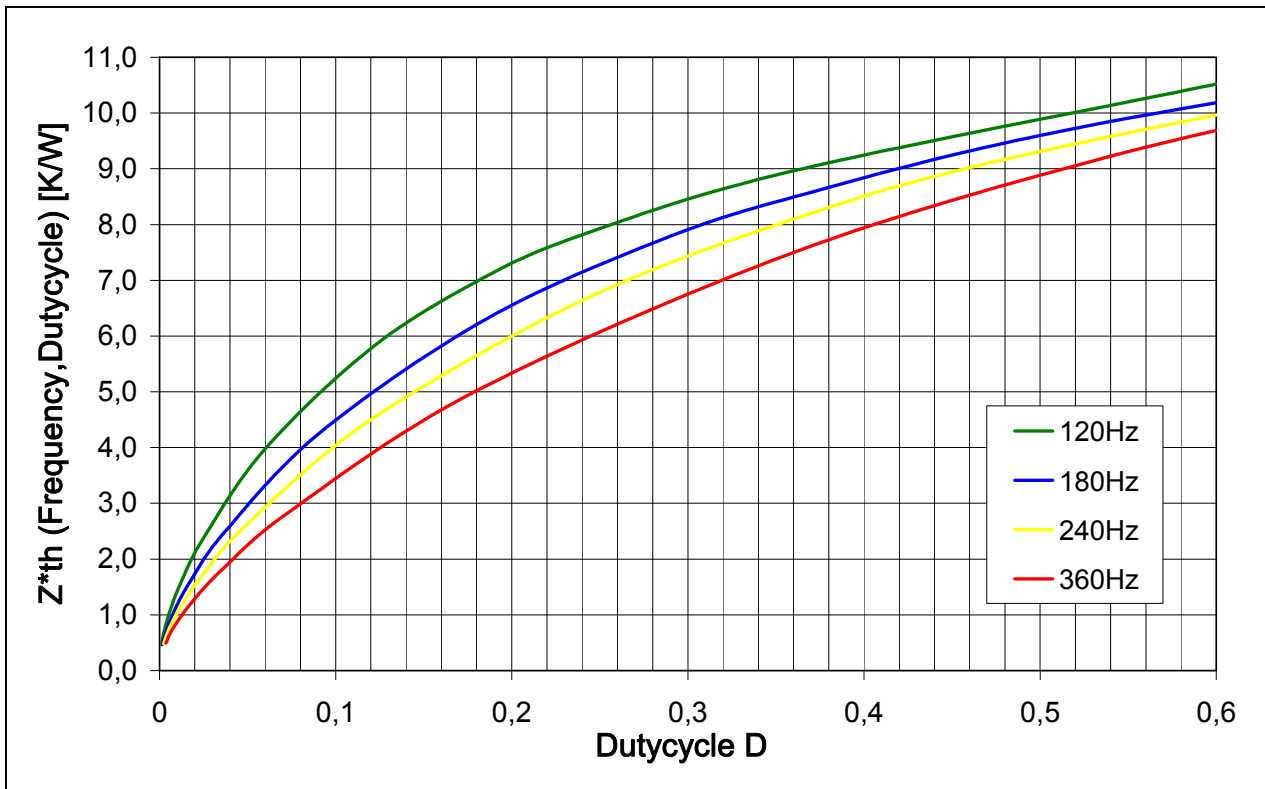


Figure 3: Thermal resistance for OSTAR® Projection module, pulsed operation of 1 chip

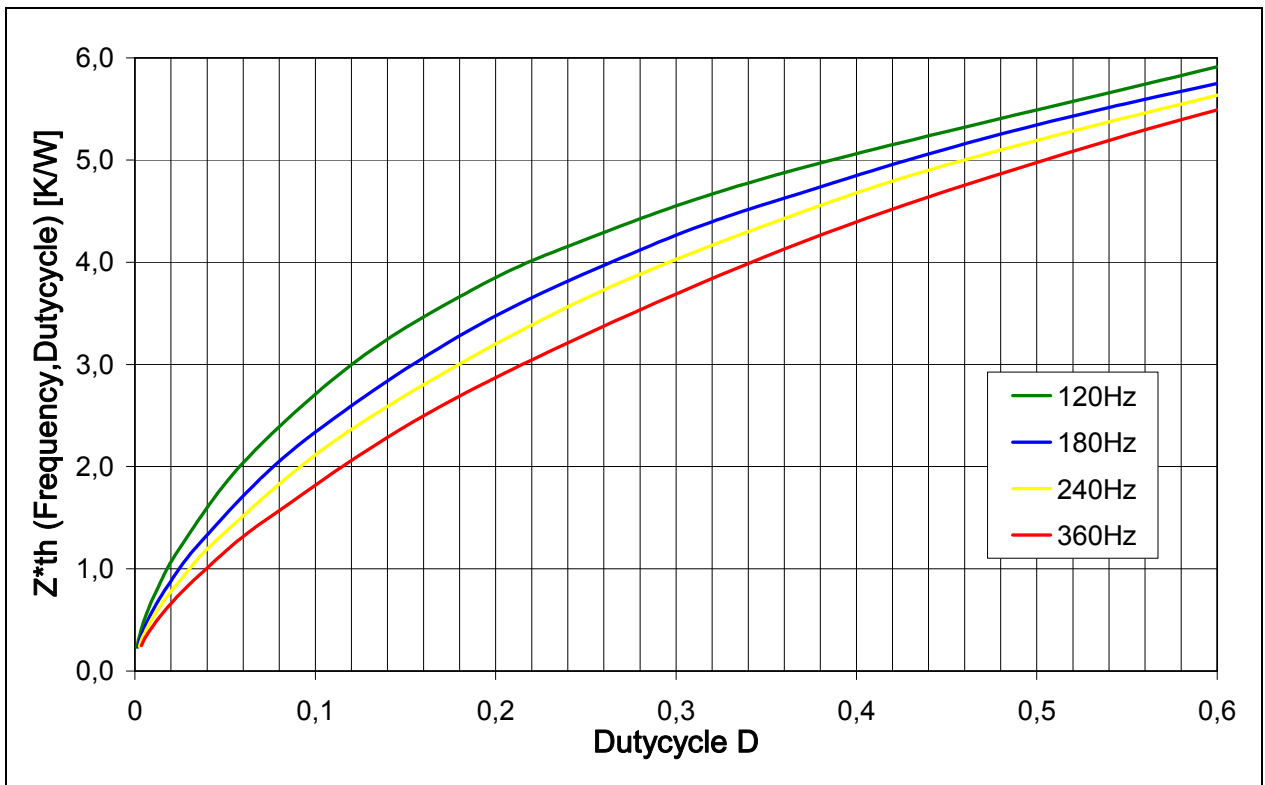


Figure 4: Thermal resistance for OSTAR® Projection module, pulsed operation of 2 chips

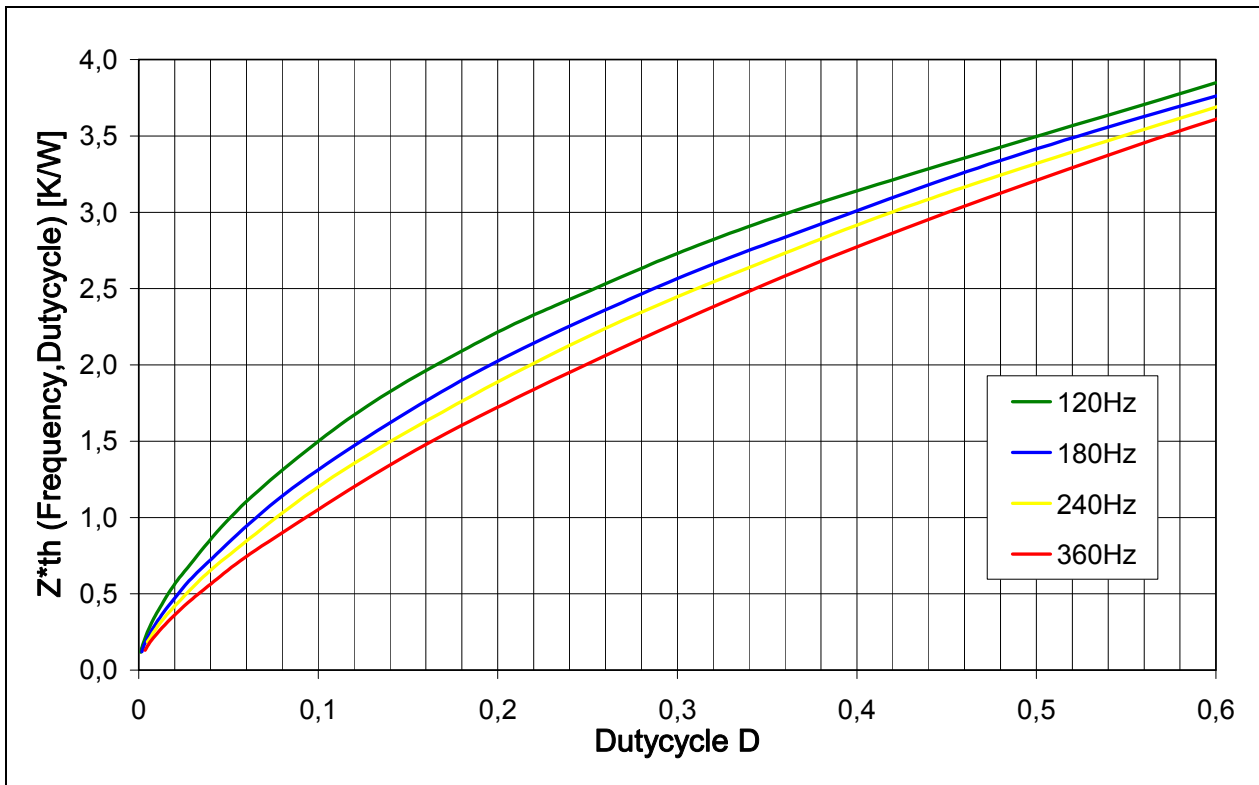


Figure 5: Thermal resistance for OSTAR® Projection module, pulsed operation of all 4 Chips

Influence and Consequences of Thermal Management

To achieve reliability and optimal performance of LED light sources like the OSTAR® Projection, proper thermal management is necessary.

Basically, there are two principal limitations for the maximum allowable temperature, both specified in the datasheet.

Firstly, the maximum allowed board temperature may not be exceeded, i.e. 85°C for the OSTAR® Projection. Secondly, the junction temperature may not rise above the allowed maximum, i.e. 125°C for the OSTAR® Projection.

In general, the heating up of the OSTAR® Projection results from two sources; one has an external origin (existing ambient temperature) and the other an internal one (current dependent power dissipation).

From this, it follows that not every mode of operation is allowed at a given ambient temperature. In the datasheets, the maximum allowed currents for continuous and pulsed operation are given at two ambient temperatures.

For all cases in between, the maximum driving conditions can be estimated from interpolation of the curves or by the use of thermal replacement circuits as described in the sections above.

Influence of Junction Temperature

Basically, the maximum allowable junction temperature should not be exceeded, since this can lead to irreversible damage to the LED and spontaneous failure. Due to the fundamental physical interdependencies which arise during the operation of light emitting diodes, changes in the junction temperature T_j within the allowable temperature range have an effect on several LED parameters.

These effects are reversible in nature.

The forward voltage, luminous flux, wavelength (color) and lifetime of the LED are all influenced by the junction temperature.

Depending on the given requirements, this can finally affect the application.

Influence of Forward Voltage V_f and Luminous Flux Φ_v

For LEDs, an increase in junction temperature leads to a decrease in the forward voltage V_f (Figure 6), as well as a reduction in luminous flux Φ_v (Figure 7).

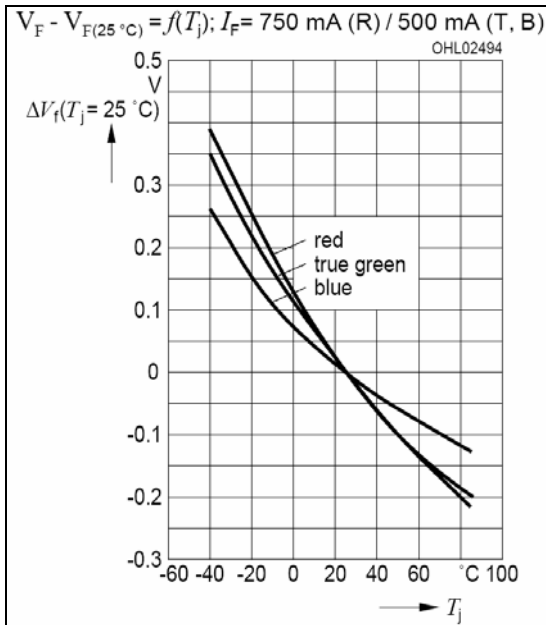


Figure 6: Relative Forward Voltage vs. Junction Temperature (e.g. OSTAR® Projection LE RTB-A2A)

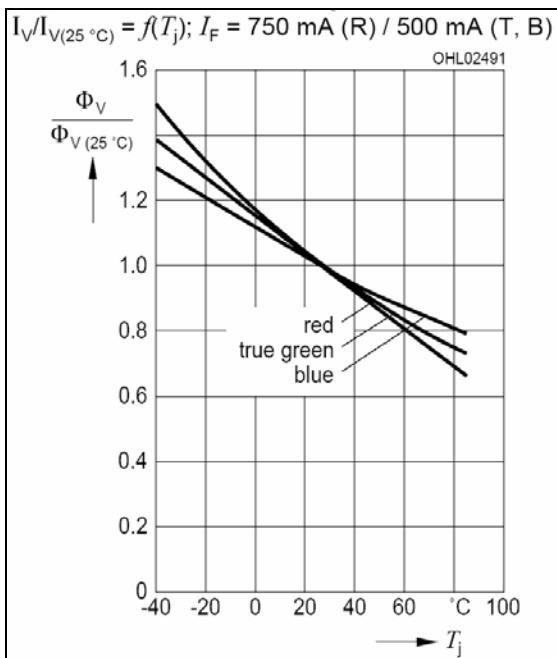


Figure 7: Relative Luminous Flux vs. Junction Temperature (e.g. OSTAR® Projection LE RTB-A2A)

In this case, the resulting changes are reversible. That is, the output values return to their original level when the temperature change is reversed.

For the application, this means that the light output increases with a decrease in the junction temperature T_j .

Wavelength (λ_{peak} and λ_{dom})

The influence on the wavelength by a change in junction temperature appears as a reversible shift in the output values. The amount of the shift can be calculated by means of the respective temperature coefficients (Table 1).

An increase in temperature to 40°C, for example, leads to a shift of the peak wavelengths in the red range of nearly 6 nm from 634 nm to 640 nm and a shift of the dominant wavelengths of 3.2 nm (625 nm → 628 nm).

This shift leads to a change in the color settings and appearance, and can have an influence on the application, depending on the given requirements.

	Temperature coefficient [nm/K]		
	R	G	B
TC λ_{peak}	0.14	0.05	0.05
If = 750mA (R), 500mA (G,B) -10 < T < 100 °C			
TC λ_{dom}	0.08	0.01	0.02
If = 750mA (R), 500mA (G,B) -10 < T < 100 °C			

Table 1: Typical Temperature Coefficient of Peak Wavelength λ_{peak} and Dominant Wavelength λ_{dom} (e.g. OSTAR® Projection LE RTB-A2A)

Due to the various temperature dependencies of the luminous flux and the different wavelengths for red, green and blue light, the white point generally shifts with a change in temperature. Depending on the application, it must be determined if this shift can be tolerated, or that appropriate measures can be taken to avoid or at least compensate for temperature related effects.

Reliability and Lifetime

Moreover, regarding aging, reliability and performance, driving an LED at its maximum allowed junction temperature is not recommended. With increasing temperature, the lifetime of the module decreases and the probability of spontaneous failures increases.

Practical Application Examples

The following section describes various possibilities for thermal management of the OSTAR® Projection light source.

The primary goal of the development was to minimize the size of the cooling element. The appropriateness of each design was verified by a thermal simulation (Flowtherm). As a basis for the simulation, the following drive parameters were chosen for the semiconductor (Table 2), with a total power dissipation for the OSTAR® Projection light source of 9.45 W, a thermal resistance of 5 K/W and an ambient temperature of 50°C.

Chip	I_F [mA]	U_F [V] @ I_F	P_{Chip} [W]
Red	750	2.8	2.45
Green	700	3.5	1.98
Blue	700	3.5	2.45

Table 2: Basic data for the chips used

OSTAR® Projection Light Source with a Heat Sink in DC Operation

The simplest and least susceptible cooling method is the use of a heat sink (Figure 8). Here, the OSTAR® Projection LED is mounted to the heat sink with screws. In order to achieve good heat transfer between the ceramic and the heat sink, a heat transfer foil or paste is most often used in practice. For the simulation, an optimal heat transfer from the module to the heat sink was assumed.

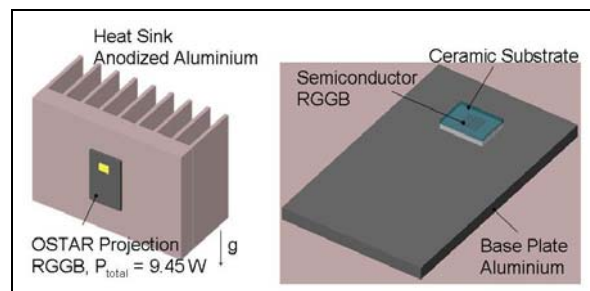


Figure 8: Construction of OSTAR® Projection with heat sink

Since the heat transfer only occurs by free convection, the heat sink must have a certain minimal size.

Figure 9 shows the results of the thermal simulation for a simple heat sink with minimal dimensions. As the temperature distribution diagram shows, a maximum junction temperature of 125°C was reached for the semiconductor chips. In this case, operation within the given parameters is still allowed.

In order to achieve a lower junction temperature, a more efficient heat sink must be used, or in general, a heat sink with lower thermal resistance must be used. For the application, this would lead to increased weight and/or costs.

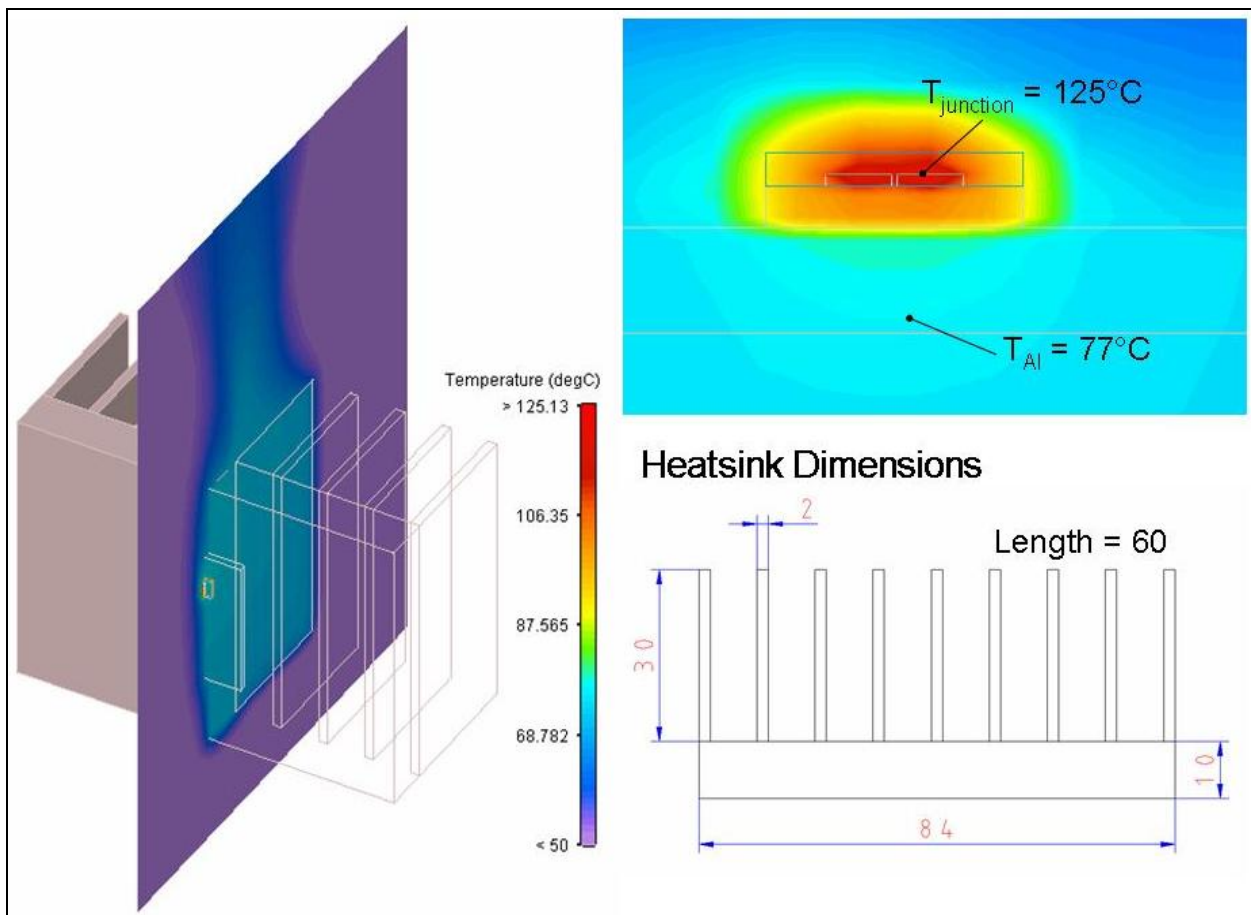


Figure 9: Simulation results for OSTAR® Projection with minimal heat sink

OSTAR® Projection Light Source with Heat Sink and Forced Convection in DC Operation

Another possibility is the operation of the light source with a heat sink and forced convection by means of an additional fan, respectively.

To permit a comparison with passive cooling and to show the influence of air flow, the same heat sink was used as in the first simulation.

The results show that even a low air flow velocity leads to a significant reduction in the junction temperature.

In practice, this means that through the use of an additional fan, the junction temperature can be stably maintained at a significantly reduced level.

This also means that in conjunction with a fan, the size of the heat sink can be reduced.

OSTAR® Projection Light Source with Minimized Heat Sink in DC Operation

In a further step, it was determined how small the entire heat sink could be reduced with the use of optimal standard components.

Figure 11 shows the simulation results for a heat sink with a length and width of 30 mm and a total height of 20 mm. The unit consists of a heat sink and cooling fan.

With the given parameters, a junction temperature of 115°C was reached, lying significantly under the maximum allowable value of 125°C.

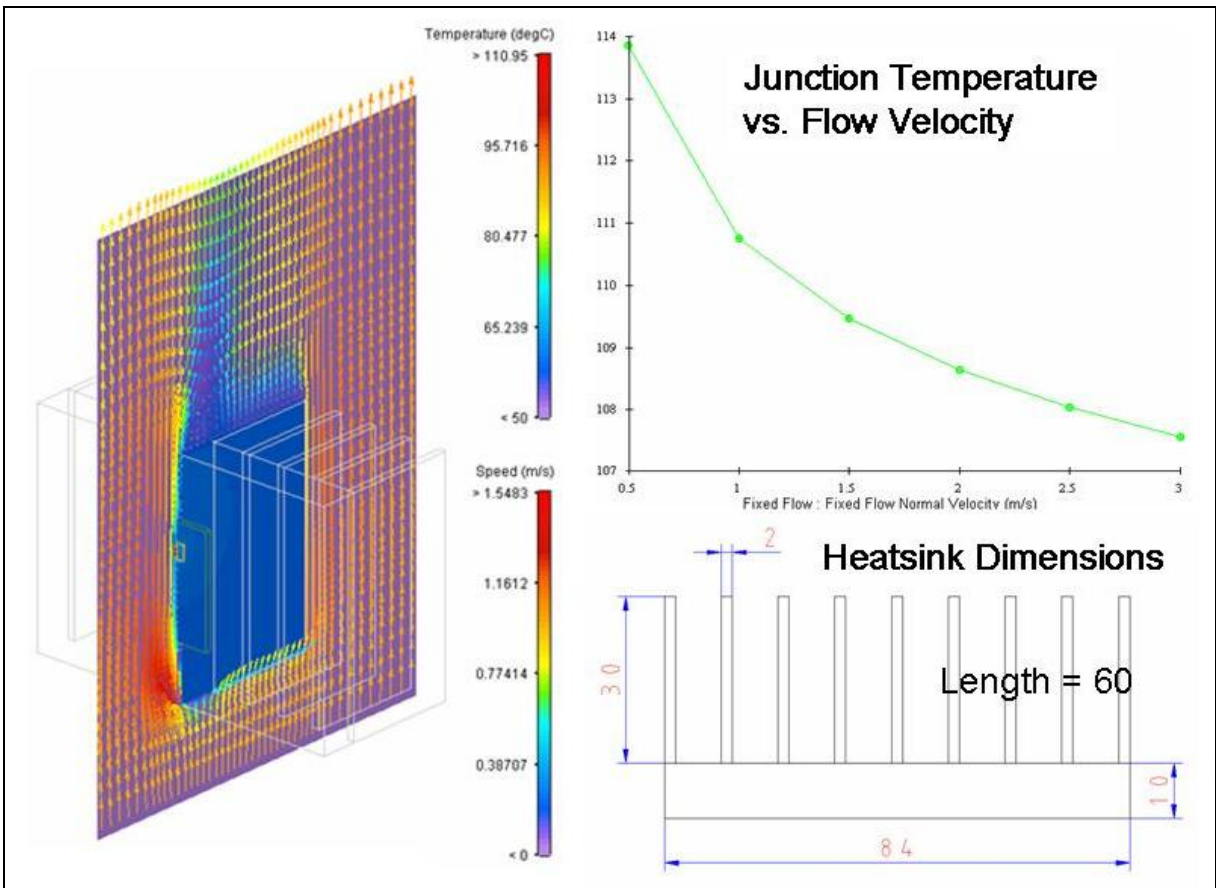


Figure 10: Simulation results of OSTAR® Projection with heat sink and fan

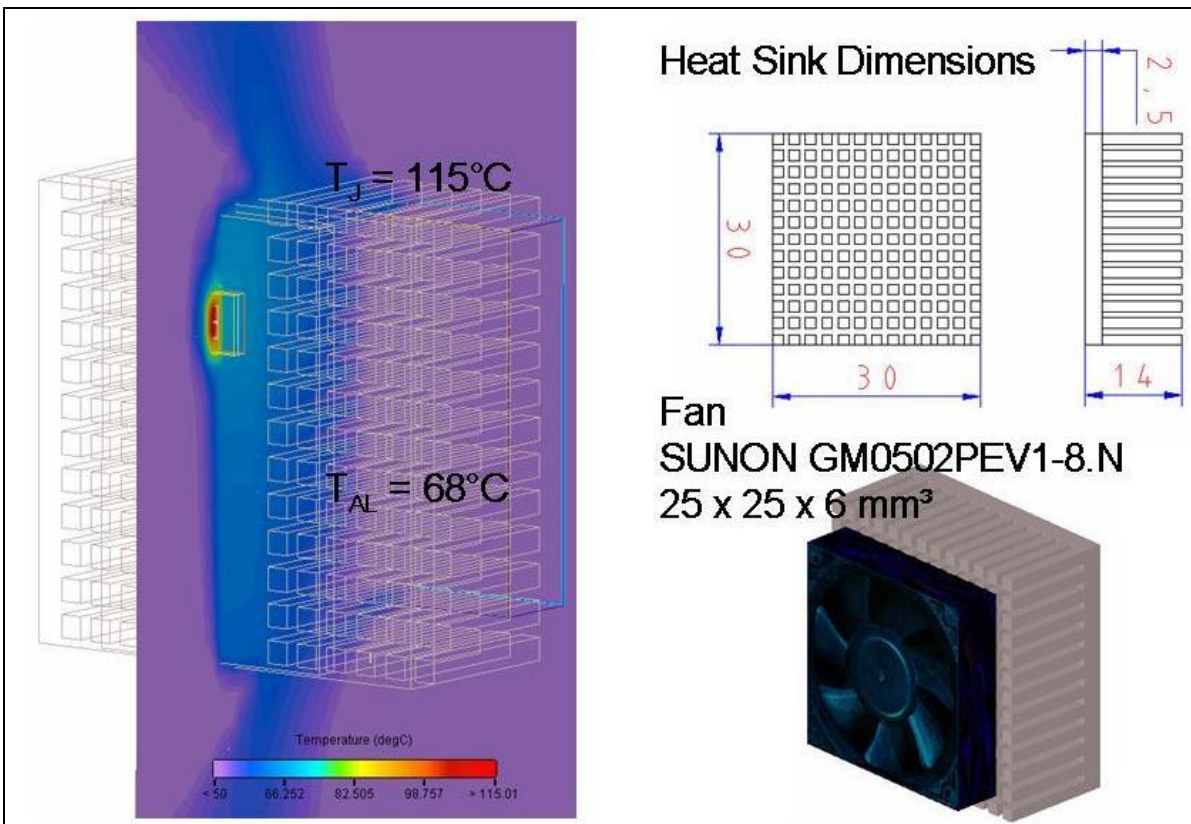


Figure 11: Simulation results of OSTAR® Projection with a minimized cooling element

OSTAR® Projection Light Source with Minimized Cooling Element in Pulse Mode

Since the light source is operated in pulse mode in a majority of applications, it was further determined whether the minimal cooling element was also suitably dimensioned for typical operation in pulse mode.

As a first step, the average temperature and temperature field of the cooling element was calculated by means of average heat dissipation.

Figure 12 shows the simulation results for the temperature field of the cooling element. For the pulse parameters used, the aluminum base plate yields a temperature of 65°C.

Chip	I_F [A]	U_F [V] @ I_F	Duty cycle	Avg. P_{Chip} [W]	Max. P_{Chip} [W]
Red	1.4	3.7	0.3	1.55	5.18
Green	1.2 (two chips parallel driven)	4.8	0.4	2.3	5.76
Blue	1.4	5	0.3	2.1	7

Table 3: Basic semiconductor chip data for transient simulation

As a basis for the transient simulation, the semiconductor chip pulse parameters were selected at an ambient temperature of 50°C and a frequency of 180 Hz (Table 3).

The transient simulation for calculation of the individual junction temperatures occurred in two steps.

From the temperature of the base plate, electro-thermal and transient thermal simulations were carried out, in which the second step showed the temperature difference and the time dependent course of the individual junction temperatures (see Application Note: “Transient Thermal Simulation of OSTAR® Projection using PSpice”).

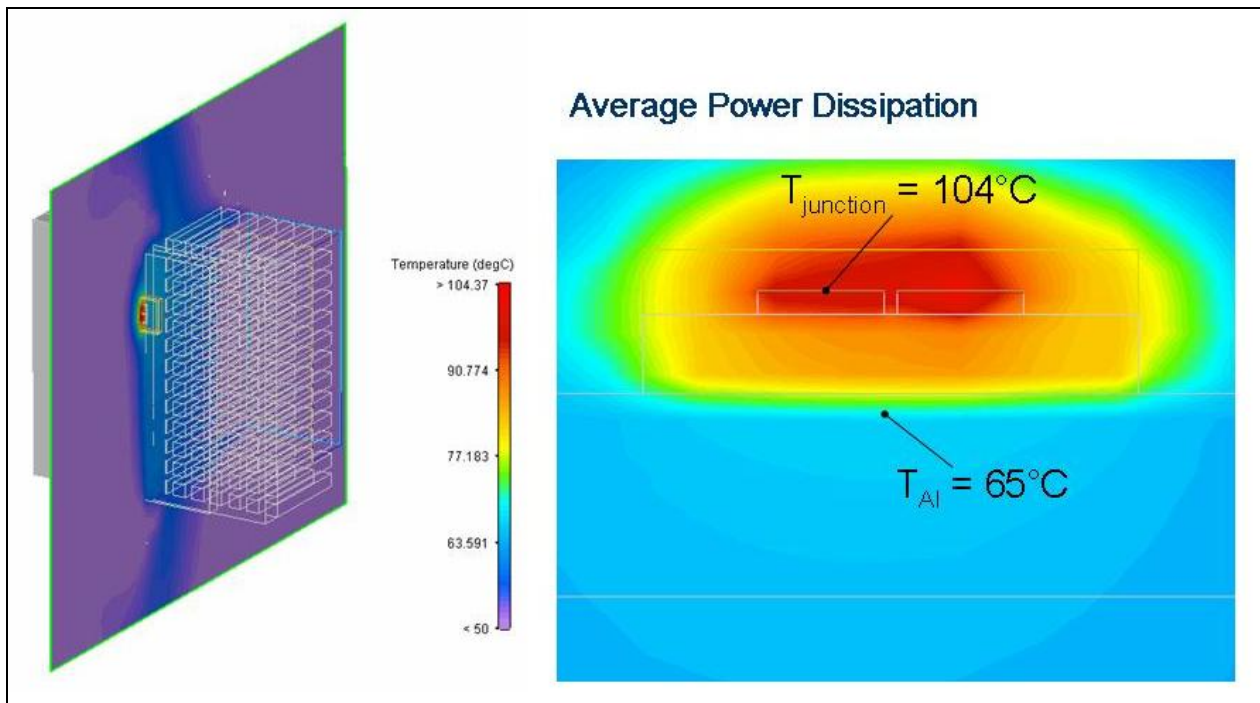


Figure 12: Simulation results of OSTAR® Projection in pulse operation, average temperature level

For the semiconductor chips, a junction temperature of

$T_{J,red} = 113^{\circ}\text{C}$
 $T_{J,green} = 121^{\circ}\text{C}$
 $T_{J,blue} = 123^{\circ}\text{C}$

and an individual time dependent temperature curve was obtained (Figure 13).

Since real surfaces always exhibit a roughness at the micro level and therefore are never perfectly smooth, physical contact between two surfaces only occurs at isolated points. In between, air pockets are formed. Approximately 99% of the surface is separated by a layer of interstitial air.

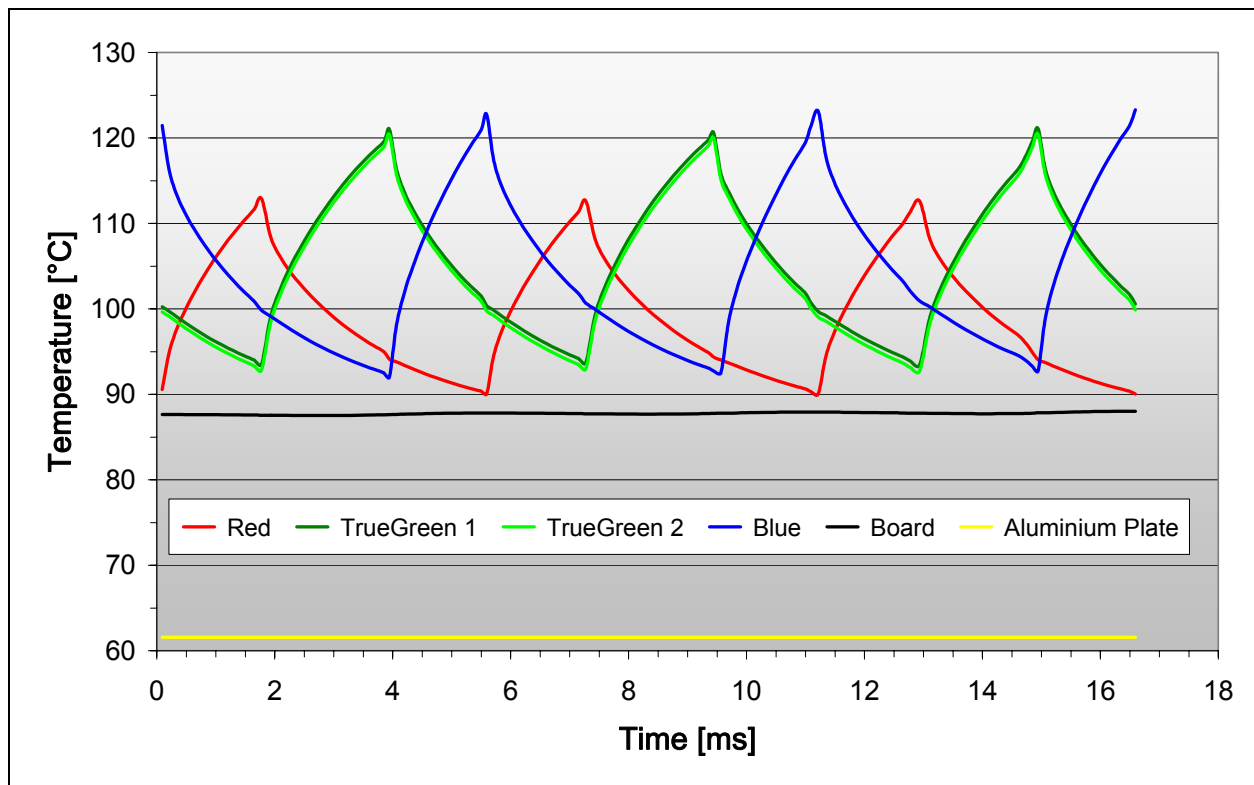


Figure 13: Simulation results of OSTAR® Projection in pulse operation, transient temperature curve

As the simulation shows, no chip exceeded the maximum allowable junction temperature limit of 125°C . Thus, the previously designed minimal cooling element is also suitably dimensioned for this pulse operation. Based on these results, the minimal cooling element can also be easily adapted to applications with lower pulse loads.

Transfer Module - Heat sink

An important aspect during development of an appropriate thermal management is the transfer of heat from the heat source to the heat sink.

Since air is a poor conductor of heat, a more conductive material should be used in order to significantly reduce the thermal resistance and to increase the heat flow between the two surfaces.

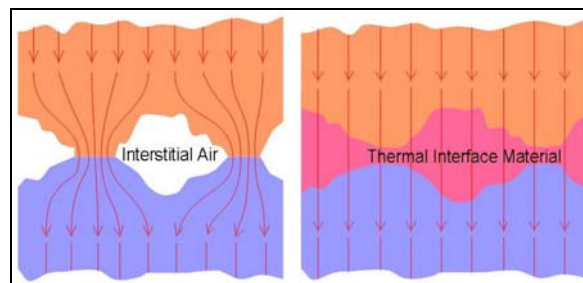


Figure 14: Heat flow without/with thermal interface material

Without an appropriate optimal interface, only a certain amount of heat transfer occurs between the components, leading to overheating of the light source. In order to improve the heat transfer and reduce the thermal contact resistance, several materials are suitable.

Thermal greases and compounds provide the lowest interface resistance, but require care in handling.

Elastomers and tapes eliminate handling problems but mostly require compressive loads even with well prepared surfaces. The success of a particular thermal interface material is dependent on the quality and processing of the material and the thoroughness of the design.

Table 4 provides a summary of the most commonly used thermal interface materials along with their advantages and disadvantages.

Description	Material	Advantages	Disadvantages
Thermal Grease	Typically silicone based with thermal conductive particles	Thinnest joint with minimal pressure	Flow out beyond the edges Messy for high volume manufacturing
Thermal Conductive Compound	Improvement of thermal grease. Compounds are converted to a cured rubber film after application at the thermal interface.	High thermal conductivity No delamination issues	Greased joints can pump out and separate with time Compounds requires curing process
Phase Change Materials	Typically polyester or acrylic materials with low glass transition temperature filled with conductive particles.	Easy handling and installation No delamination issues No curing	Requires attachment pressure Pre-treatment heating necessary
Thermal Conductive Elastomers	Typically silicone elastomer pads filled with thermally conductive particles. Often reinforced with glass fiber or dielectric films.	No pump out or migration concerns	Delamination issues Thermal conductivity is moderate
Thermal Conductive Adhesive Tapes	Typically double sided pressure adhesive films filled with sufficient particles to balance their thermal and adhesive	No curing required	Requires attachment pressure

Table 4: Thermal Interface Materials

Heat Sink

In addition to the geometric dimensions, the thermal resistance value is particularly important when selecting a suitable heat sink.

To estimate the thermal resistance of the heat sink, the following equation for DC operation can be used.

$$\frac{\Delta T}{P_{Diss, Modul}} - R_{th, Interface} - R_{th, JB} = R_{th, Heat\ sink}$$

where

$$\Delta T [K] = T_{J(unction)} - T_{A(ambient)} - T_{Safety-Factor}$$

$$P_{Diss, Modul} [W] = U_f [V] \cdot I_f [A]$$

- $T_{Junction}$ = Junction Temperature
- $T_{Ambient}$ = Ambient Temperature
- $T_{Safety-Factor}$ = Safety factor (10°C - 20°)
- U_f = forward voltage
- I_f = forward current
- $R_{th, Interface}$ = thermal resistance of interface material
- $R_{th, JB}$ = thermal resistance of OSTAR® Projection LED
- $R_{th, Heatsink}$ = thermal resistance of heat sink

In general, it can be said that the lower the thermal resistance must be to fulfill the given requirements, the more difficult and costly the construction of the thermal management becomes when only a heat sink is used.

For more stringent requirements, the use of an additional fan should be considered, in order to positively affect the behavior of the heat sink

In general, the presence of air flow or the use of a fan can help to reduce the thermal resistance of the heat sink.

Example Using the OSTAR® Projection Light Source LE B A2A:

Driving the light source with constant current $I_f = 500\text{mA}$;

$$U_{f, typ.} = 3.5\text{ V} \rightarrow \text{typ. } P_{Diss, Modul} = 7\text{ W}$$

- $T_{Junction} = 125^\circ\text{C (max.)}$
- $T_{Ambient} = 25^\circ\text{C}$
- $T_{Safety-Factor} = 10^\circ\text{C}$
- $R_{th, JB} = 5\text{ K/W}$
- $R_{th, Interface} = 0.1\text{ K/W (e.g. thermal paste)}$

$$R_{th, Heat\ sink} = \left(\frac{125 - 25 - 10}{7} - 0.1 - 5 \right) \text{ K/W}$$

$$R_{th, Heat\ sink} = 7.76\text{ K/W}$$

Using this thermal resistance value, an appropriate heat sink can now be selected from the manufacturer.

In order to safeguard the design and to verify the board or base plate temperature, the resistance value can be obtained from the NTC. Typical characteristics for the NTC are provided in the respective datasheets for the OSTAR® Projection LED.

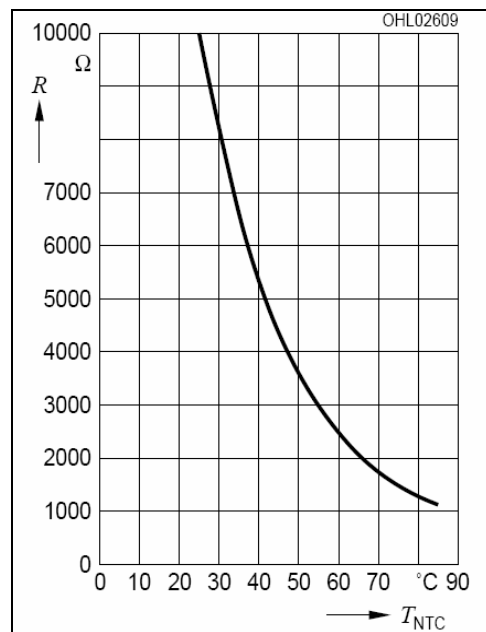


Figure 15: Typical thermistor graph (e.g. OSTAR® Projection LE B-A2A, NTC EPCOS 8502)

Summary

Designed for high power operation with currents of up to two Amperes, the OSTAR[®] Projection LED light source delivers a power dissipation of 10 W and more, depending on the operational parameters chosen.

Appropriate thermal management is imperative in order to dissipate the heat which arises and guarantee optimal performance and reliability of the module.

As the simulations have shown, the OSTAR[®] Projection can be operated with a simple heat sink of minimal dimensions.

With air flow or through the use of an additional fan, the heat sink dimensions and/or the junction temperature can be significantly reduced.

Based on generally available standard components and the specific operational conditions mentioned above, a minimally sized cooling element (heat sink and fan) was developed with dimension amounting to just a few centimeters (3 cm x 3 cm x 2cm).

In general, it is necessary and strongly recommended that in addition to a thermal simulation, a prototype of the design should be verified by means of thermal measurements.

Appendix

Heatsinks

Aavid Thermalloy
Advanced Thermal Solutions
Alutronic Kühlkörper
Fischer Elektronik

www.aavidthermalloy.com
www.gats.com
www.alutronic.de
www.fischerelektronik.de

NTC

EPCOS (NTC 8502)

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