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LED Thermal Management

Thermal Characterization

Effect of Thermal Environment

PowerPSoC Controller

Thermal Management

Comparison of Passive and Active Cooling Effectiveness

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Excessive heat has long been an issue with manufacturing LED luminaires given the fact that all components need to match or exceed their extensive lifetimes, this is especially a concern for high brightness LEDs. These ultra-high brightness LEDs are rapidly gaining popularity and finding their way into a diversity of applications – outdoor signage, architectural, accent and landscape lighting, traffic signaling, LCD backlighting, medical diagnostics instruments, airfield and aircraft interior lighting, automotive – interior and exterior, decorative and entertainment lighting, and increasingly considered even in general lighting. Ultra-high brightness LEDs offer the unique combination of long operating life, vivid saturated colors and are environmentally efficient. Given the depth of applications and market benefits, the HB-LEDs will continue to expand and therefore, their thermal issues will need to be addressed.

Thermal management is a relatively new obstacle for the lighting industry as it was historically not a factor for either incandescent or florescent lighting solutions. With either traditional option, heat could be radiated out of the luminaire as anyone knows who has burned their hand on a hot light bulb. However, LED lights emit very little heat so the heat must be dissipated through the back of the LED to insure the junction temperature of the LED is maintained at appropriate levels. Two options currently exist to resolve thermal management issues – passive cooling utilizing heat sinks and active cooling utilizing various processes. These will be compared and contrasted in further detail.

There are four main components required to design an LED luminaire: the LEDs, Optics, Electronic Driver and Thermal Management. To bring LEDs to market for general illumination, thermal management is not only needed, but is critical to the success of the project. LEDs are temperature dependant, not only for long life, but so that the maximum light output, quality and reliability of the device is preserved. Maintaining the temperature of the LEDs can have a remarkable effect on the lifetime of the LED. Reducing the junction temperature of the LED by just ten degrees can add fifty percent to the life of the LEDs as shown in Figure 1.

Proper temperature management can also improve the light output of LEDs. Reducing the junction temperature of amber LEDs can double the light output. Other colors are less sensitive, but still demonstrate a dramatic improvement. For example, reducing the temperature of a white LED from 100°C to 45°C adds up to 25% in light output.

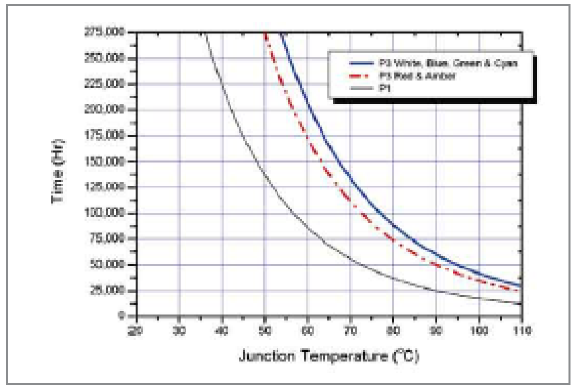

Figure 1: Lifetime vs. junction temperature (Source: Seoul Semiconductor Thermal Management Guide).

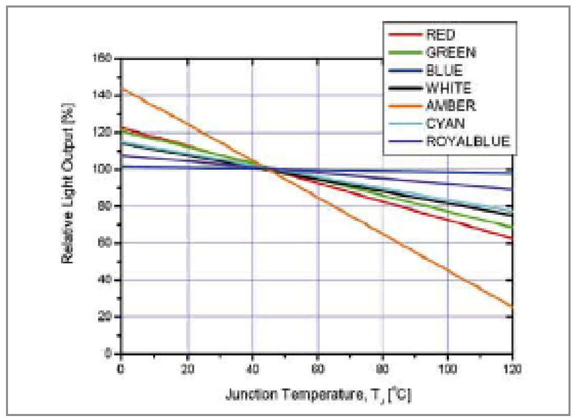

Figure 2: Relative light output vs. junction temperature (Source: Seoul Semiconductor Thermal Management Guide).

Thermal Management's Effect on the Artistic Values of Lighting Design

Thermal management, along with the LEDs, optics and electronic driver are the minimal components of an LED based luminaire. The choice of cooling solution will drive the exterior look and feel more than any other element. Heat sinks have traditionally been the first line of defense for electronics cooling, with the outcome being heat sink design has been pushed to its maximum value. In other applications such as electronics, it was convenient that the look and feel of the heat sink was not important as it was enclosed in a computer or telecom box. However, luminaire designers are exceptionally concerned with aesthetics. Indeed, a luminaire is as much a work of art as it is functional. Even in cases such as recessed can lighting where the fixture is not visible, there is still a strong justification for making the most attractive heat sinks. As one lighting designer stated, 'Lights might be installed in the ceiling, but they are sold on the table.' Inventive and artistic luminaire designs are always preferred over an unrefined approach.

How Active Cooling Enhances LED Luminaires

The ideal cooling solution for an HB LED would be effective, highly reliable, small and quiet. Heat sinks meet most of the above criteria and are an important element of the thermal solution for LED luminaires. However, the objective in employing active cooling is to allow greater design freedom of the luminaire. The diversity of form factors is greatly improved with the use of active cooling. The following three elements should be evaluated when selecting which cooling solution is best suited for the lighting design.

Size - The size of the thermal management solution can be significantly reduced utilizing active cooling. In some instances, it can be reduced by a factor of two or three that of a passive solution alone. Reducing the size gives luminaire designers the flexibility to create the most attractive designs and to be able to fit into tight ceiling enclosures or other unobtrusive applications.

Weight - The weight of the luminaire heat sink can be reduced by half or more in some applications by using an actively cooled solution. This attribute pays dividends in many ways, from lower shipping costs to easier installations allowing for the greenest designs.

Orientation – Orientation plays a bigger part when designing passive heat sinks vs. using active cooling. For example, to design the best passive solution possible for a luminaire that is vertical, ideally you would use a heat sink with vertical fins. However, if the angle of that same luminaire is changed to 45° or 90°, it measurably changes the optimal heat sink design. Conversely, with an active cooling solution, the orientation has nominal impact on the design.

Case Study – LED Downlight System

The Philips Fortimo LED DLM system is an LED breakthrough in energy efficiency in a higher lumen package. It is specifically designed to incorporate improved LED efficiencies for functional general lighting. One of the most important factors to ensure the success of LED DLM system is the custom thermal solution embedded in the system. There are two reference design options for the Fortimo system, a passive heat sink (Marston 94DN, 150mm length heat sink) and a SynJet® Universal DLM active solution, see Figure 3 and Figure 4 for reference.

In basic terms, passive heat sinks dissipate heat through natural convection. For passive heat sinks to perform to their full capacity, it is critical to size the heat sink with the optimum fin spacing, length and placement in the proper orientation. Conversely, active heat sinks are equipped with the addition of an air movement device, such as a synthetic jet, to increase the heat dissipation by forcing an increased amount of air through the heat sink, also known as forced convection.

The Convection heat transfer equation is:

$q = h*A*(Ts - Ta)$

- A is the surface area;
- Ts is the surface temperature;
- Ta is the ambient temperature;
- h is the heat transfer coefficient, depending on the fluid flow and the physical properties of the air and heat sink.

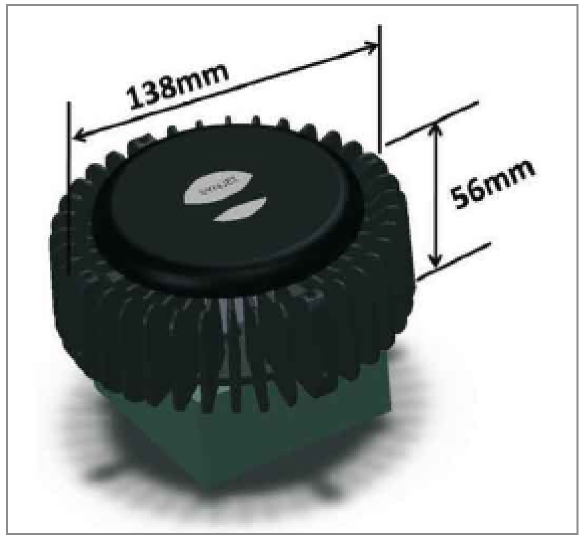

Figure 3: Philips Fortimo reference active heat sink design - Nuventix SynJet active solution.

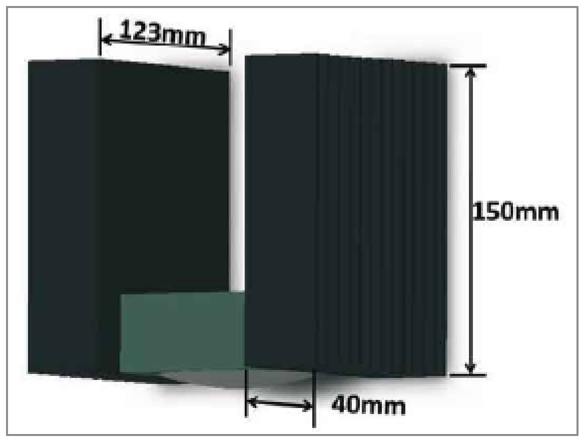

Figure 4: Philips Fortimo reference passive cooling heat sink design.

The driving mechanism for natural convection is the change in density of the air due to heating; i.e. buoyancy driven fluid flow. As we all know, hot air rises and it is this motion of the air that removes the heat as it moves along the fin surfaces. With the proper heat sink design, natural convection can be a very effective; however, in most practical applications the velocity of the fluid flow is low and correspondingly so is the heat transfer coefficient.

On the other hand, forced convection relies on an external mechanism, such as a synthetic jet (SynJet), to force the air through the fins and thereby removing the heat. With forced convection, the velocity of the air moving through the fins can be greatly increased above that of natural convection, thus increasing the heat transfer coefficient (Table 1).

Process	h, W/m2K
Natural Convection of Gases	2 - 25
Forced Convection of Gases	25 - 250

Table 1: Typical values of the convection heat transfer coefficient h for natural and forced convection of gases(Fundamentals of Heat and Mass Transfer 5th Edition, Incropera & DeWitt).

The value of h is a strong function of the velocity and regime of the flow, i.e. whether it is laminar or turbulent. SynJet flow is turbulent and has a high heat transfer coefficient as indicated in the chart below which compares dynamically similar flow for Synthetic jet channel flow and fully developed flow for the same Reynolds number. Note the chart shows the non-dimensional Nusselt number vs. Reynolds number, where the Nusselt number is proportional to h, while the Reynolds number is proportional to the air velocity V.

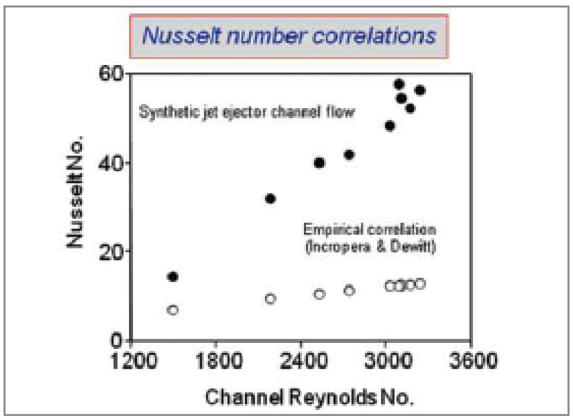

Figure 5: Nusselt number correlation to Channel Reynolds number.

The testing results below measure the cooling capability of a passive heat sink in comparison to an actively cooled heat sink for the Philips Fortimo LED DLM system. Rather than using h as a direct comparison for the thermal solutions being tested, the thermal resistance from the Fortimo case to ambient was calculated, Rc-a.

$R_{c-a} = (T_c - T_a)/Q$

Tc is the Fortimo case temperature;

Ta s the ambient temperature;

Q is the power dissipated into the heatsink

Test Set Up

Thermal tests were conducted on the reference designs to compare the differences in size, weight, and orientation dependence for equivalent thermal performance of a passive solution and an active cooling solution. A Fortimo package was fitted with a heating element to represent the heat load of the LEDs into the package. The heater was used in lieu of an actual Fortimo equipped with LEDs in order to accurately measure the power dissipated into the package. A 2000 lumen Fortimo dissipates ~ 40W, so 40W was used as the input power to the heater.

T-type thermocouples were used to measure temperatures. One thermocouple was embedded into the case of the Fortimo package to measure Tc and an additional thermocouple was placed in close proximity to measure the ambient temperature Ta, see Figure 6. A data acquisition system was used to record and monitor the temperatures to ensure the thermal solutions were allowed to reach steady state, see Figure 7 for a typical temperature profile measured during the testing. The steady state temperatures were averaged and used to calculate the delta between Tc and Ta, and Rc-a was calculated according to the equation above.

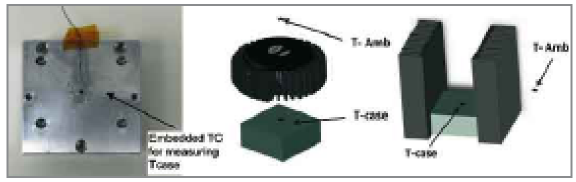

Figure 6: Thermocouple locations.

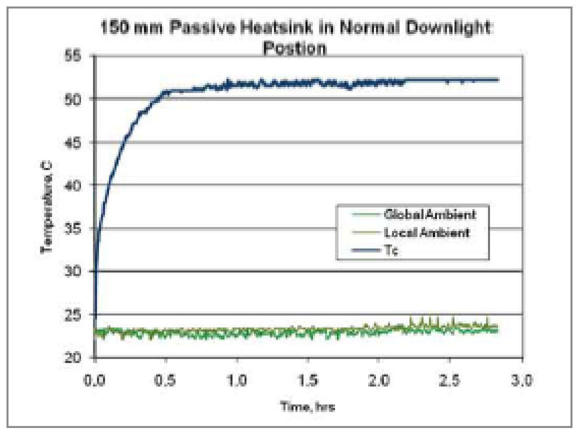

Figure 7: Sample temperature profile of thermal solution achieving steady state.

Bergquist GP2500S20 (0,020 inches thick) was used to ensure consistent good thermal contact between the heatsinks and the Fortimo module, see Figure 8.

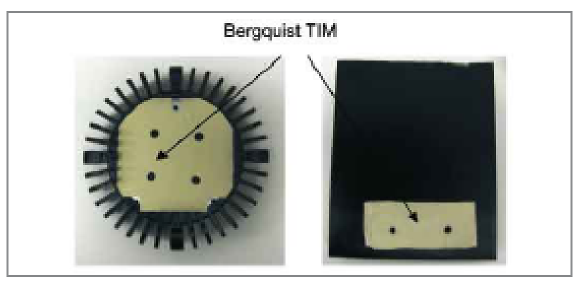

Figure 8: Bergquist GP2500S20 installed on heatsinks.

Several cases were tested to determine Rc-a for both thermal solutions in different operating orientations:

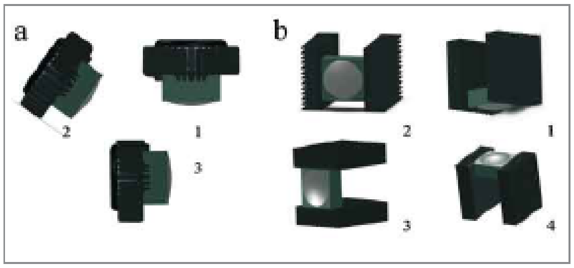

Figure 9: Active heat sink testing orientation (a – 1. normal down light position, 2. 45 degree, 3. 90 degree) and passive heat sink testing orientation (b – 1.normal down light position, 2. 90 degree side, 3. 90 degree top down, 4. down Light facing up).

The chart in Figure 10 below shows the results of the SynJet active solution and the 150mm length Marston 94DN. The SynJet active solution has a consistent Rc-a regardless of the heat sink orientation, however, the passive heat sink demonstrated thermal degradation and increase in Rc-a up to 15%.

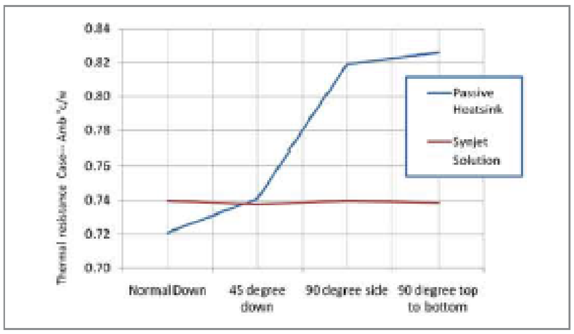

Figure 10: Thermal resistance in various heat sink orientations.

A second study was conducted to determine the required length for the Marston 94DN heat sink to achieve equivalent performance as the SynJet DLM II HP performance, which has an Rc-a of 0,63°K/W.

A curve of the Rs-a vs. length was generated for the Marston 94DN heat sink and is shown in Figure 11. In addition, Figure 12 shows curves of modeled and measured Rc-a vs. length.

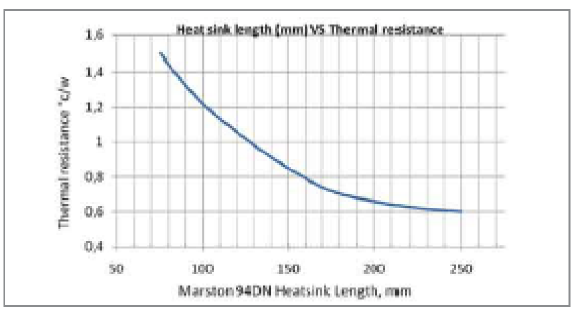

Figure 11: Rs-a vs. heat sink length (Source: Marston 94DN Datasheet).

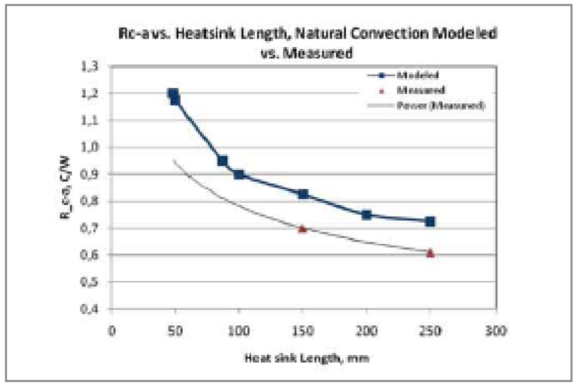

Figure 12: Modeled and measured Rc-a vs. heat sink length.

As both curves show, the benefit of reducing thermal resistance by increasing heat sink length starts to diminish after ~ 175mm. The heat sink length needs to increase to 250mm in order to obtain a comparable performance to that of the SynJet Universal DLM High performance setting.

As seen in the table below, the overall mass for the 150mm passive heat sink is 1400g compared to 600g for SynJet active solution, which is ~140% heavier. In addition, the passive heat sink volume is ~ 75% larger than the SynJet solution.

These differences are dramatically increased when increasing the length of the passive heat sink in order to match the Universal DLM High Performance Setting.

Heat Sink (HS) Type	HS Vol. (cm³)	Δ%	HS plus Module Vol. (cm³)	Δ%	Weight (g)	Δ% t
SynJet Active Cooler	1066		1714		606	
Passive HS (150mm)	1476	38%	3007	75%	1435	137%
Passive HS (250mm)	2460	131%	5012	192%	2392	295%

Figure 13: Picture showing 250 mm and 150 mm passive vs. SynJet Universal DLM.

Conclusions

There are clear benefits to passive heat sink cooling – reliability, low power and silent acoustics. However, with the advent of LEDs and high brightness LEDs, passive heat sinks alone cannot dissipate sufficient heat to resolve current LED thermal management issues. Given the designer requirements for small size and diversity of form factors, the addition of active cooling is a key consideration. The combination of active cooling and a small, specialized heat sink create a synergy proved most efficient in meeting all of the luminaire designer requirements.