USING INTEGRATED PLANAR THERMOSYPHON PCBs TO ENHANCE COOLING OF HIGH BRIGHTNESS LEDs

High power LED lighting systems bring with them a lot of promise and numerous challenges. The advantages of LED lamps are compact size, long life, easy maintenance, rugged construction, ability to withstand cold temperature, reduced IR radiation and increased performance. Thermal management, cost competitiveness and quality are the challenges faced in widespread usage of such lamps. Thermal management is a notable roadblock to the implementation of such systems. There is 70 – 80 % of the electrical power in a high brightness LED is converted to heat which has to be efficiently dissipated. Poor thermal design leads to high operating temperatures resulting in reduced brightness, shift in wavelength (color) and reduced life. Table 1 shows the potential advantages and the challenges of a LED lighting system. [1]

	Incandescent	Flourescent	Metal Halide	LED
Visible Light	8%	21%	27%	20-30%
IR	73%	37%	17%	0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	20-30%
Non-Radiant Heat	19%	42%	37%	70-80%
Total Energy	100%	100%	100%	100%

Table 1. Power Conversion for White Light Sources [1]

High brightness LEDs are used in LED lamps, display backlights, camera flashes and many other such applications, with heat flux reaching in excess of 80 W/cm^2. Thermal management challenges in such systems are twofold. While one is to maintain uniform temperature across LED junctions in an array, the other is to have high in plane heat spreading at the heat sink and PCB levels.

Thermal management of high power LEDs are being researched at the chip package, the Printed Circuit and the system level. At the chip level, research is mainly focused on reducing the package thermal resistance of the LED, LED array optimization and material selection for better performance. At the board level, thermal management research is mainly focused on solder material, improving bonding methods and PCB design for improved thermal performance. One idea is to use heat pipes at the circuit board level to improve the heat spreading [2]. At the system level, heat sink optimization, utilization of vapor chambers, heat pipes and in some extreme cases active and or liquid cooling options are being explored.

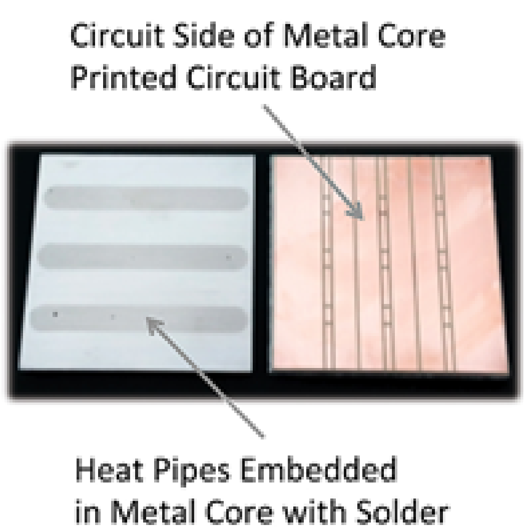


Figure 1. Heat Pipes Embedded in a PCB [2]

The heat pipes can be either completely embedded in the PCB or can be extended from the PCB and attached to an external heat sink. IR images and thermography show the improved spreading of the heat on the PCB as seen in Figure 2. The temperature scale in the IR image is set from 58°C to 68°C.

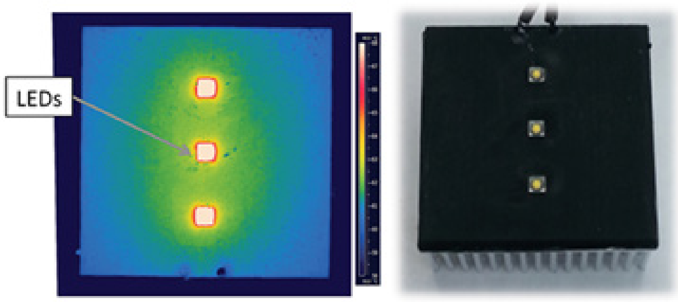


Figure 2. Heat Pipes Embedded in a PCB [2]

Bonner et al. [1] have focused on improving the heat dissipation from the LED package to the PCB using thermosyphons. While the concept of a planar thermosyphon to enhance heat transfer by itself is not new, integrating it into a printed circuit board is innovative and appears to be a promising technology.

A typical thermosyphon is, simply put, a highly efficient heat spreader. The heat from the electronic device attached to it vaporizes the working fluid inside the thermosyphon thereby limiting the temperature rise. Vapor then condenses back to liquid at the condenser section which is cooled by an external heat sink. In this case, researchers used a dielectric fluid as the working fluid which provided the electrical isolation necessary to prevent short circuiting, eliminating the need for a ceramic substrate separating the thermal pad from the electrical circuitry. The thermal resistance of this thermosyphon/PCB decreased by more than 50% from a regular Metal clad PCB and 86% more than a regular FR4 PCB.

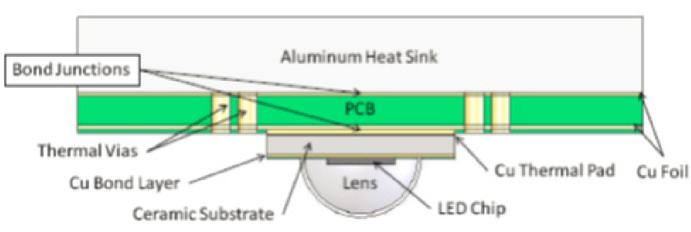


Figure 3. A Typical Surface Mount LED on a Typical PCB [1]

Figure 3 shows a typical surface mount LED where the PCB can be either FR4 or MCPCB.

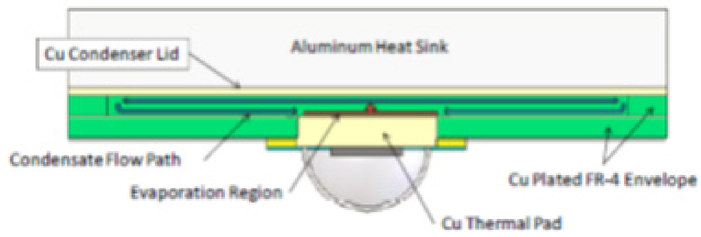


Figure 4. The Design Concept of a Thermosyphon Inside a PCB [1]

Figure 4 shows the novel concept researchers of [1] propose.

The design that incorporates the thermosyphon, replaces the typical dielectric layer, which inherently has low thermal conductivity values, by an enclosed vapor space filled with dielectric fluid. Thermosyphons work very well when gravity aids the flow of condensate back to the evaporator section. This agrees well for LED applications where most of the artificial lighting systems are in the form of downlighting. For applications where this is not the case, a thin layer of wick over the evaporator area can used to provide the capillary action which is needed to drive the liquid against the gravity field. It is also worthwhile to note that the thin layer of wick enhances the boiling heat transfer since there are extra nucleation sites.

The authors used a CREE XLamp LED for their prototypes. The typical heat flux for these packages varies from 18 to 64 W/cm^2 over an area of 4.25 mm^2. Cree suggests the use of MCPCB's and FR-4 PCB's with thermal vias as shown in figure 5a and 5b.The cross sectional view of the prototype design, as seen in figure 6, clearly shows a copper plug in the middle of a two side copper clad FR-4 PCB to simulate the LED thermal pad. The PCB is bonded to a copper chamber to form the vapor space which houses the dielectric working fluid. The thermal performance of the Planar Thermosyphon/PCB, the MCPCB and a generic FR-4 PCB were analyzed using CFD modeling. Tables 2-4 show the configuration of the three PCB's that were evaluated for this comparative study.

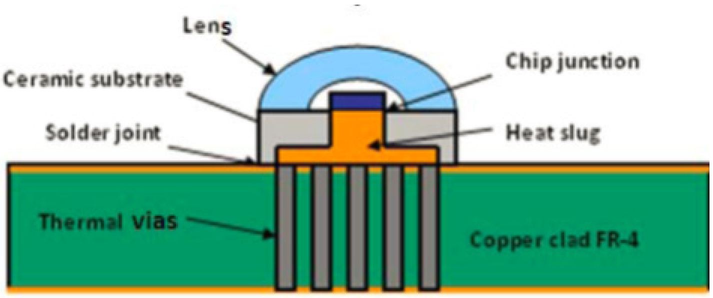


Figure 5a. LED Chip Package Mounted on a FR4 PCB as Suggested by Cree [1]

Component	Thickness (µm)	Thermal conductivity (W/m·K)
Top layer copper	70	398
PCB dielectric	100	2.2
Al plate	1588	150
Total	1758	--

Table 3. Configuration of a Metal Core PCB (Surface Area 270 mm²) With Thermal Vias [1]

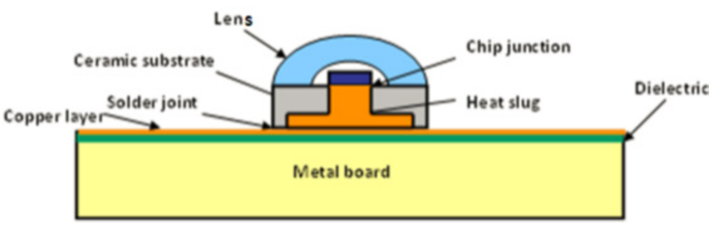


Figure 5b. LED Chip Package Mounted on a Metal Core PCB as Suggested by Cree [1]

Component	Thickness (µm)	Thermal conductivity (W/m·K)	Heat transfer coefficient (W/m²·K)
Copper plug (area 3.3 x 1.65mm)	728	398	--
Top layer copper	70	398	--
FR-4 dielectric	588	0.2	--
Bottom layer copper	70	398	--
Evaporator surface	--	--	20,000
Vapor surface	600	100,000	--
Condenser surface	--	--	10,000
Copper chamber	1,000	398	--
Total	1728	--	--

Table 4. Configuration of a Planar Thermosyphon PCB (Surface Area 270 mm²) [1]

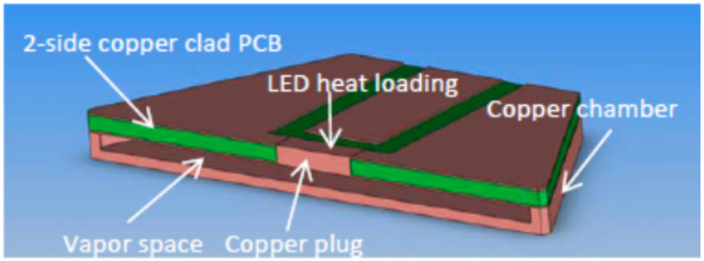


Figure 6. Cross-Sectional View of the Model of a Planar Thermosyphon PCB [1]

For the CFD simulations, a finned heat sink was added to the back side of the model along with forced air cooling. The tabulated results are presented in Table 5 and the temperature distribution over the different PCB's under a heat load of 1 W is presented in Figures 7a – 7c.

Component	Thickness (µm)	Thermal conductivity (W/m·K)
Top layer copper	70	398
FR-4	1588	0.2
Filled vias (SnAgCu)	1588	59
Bottom layer copper	70	398
Total	1728	--

Table 2. Configuration of a FR-4 PCB (Surface Area 270 mm²) With Thermal Vias [1]

	Q_{in} = 1E	
	ΔT	$R = \frac{\Delta T}{Q_{in}}$
FR-4 PCB	26.6	26.6
MCPCB	7.2	7.2
Thermosyphon PCB	3.7	3.7

Table 5. Thermal Resistances Calculated Based on CFD Results [1]

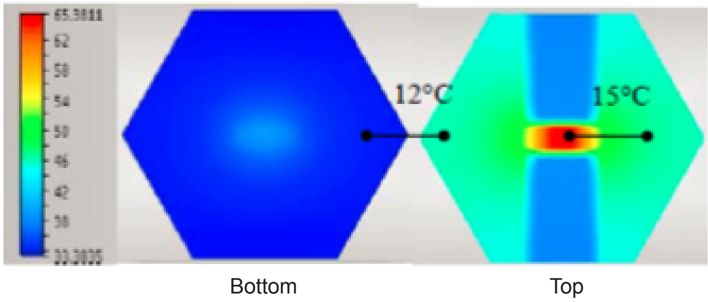


Figure 7a. Temperature Distribution of the Top and Bottom Surface of a FR4 PCB From CFD Simulations [1]

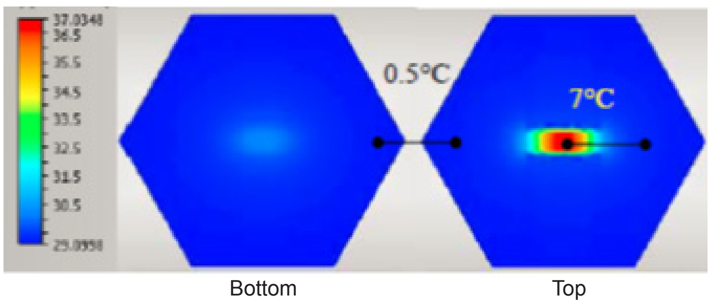


Figure 7b. Temperature Distribution of the Top and Bottom Surface of a MCPCB From CFD Simulations [1]

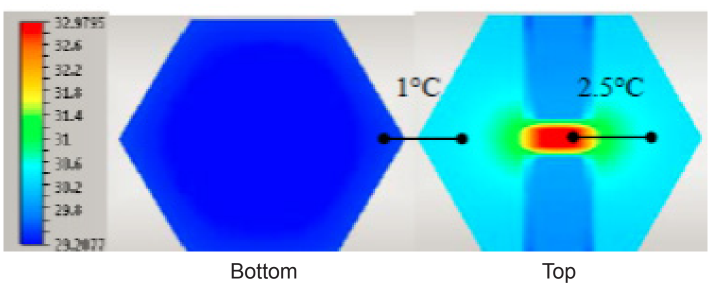


Figure 7c. Temperature Distribution of the Top and Bottom Surface of a Planar Thermosyphon PCB From CFD Simulations [1]

The CFD results shows clearly that while the FR-4 PCB has poor thermal performance in both the axial and Planar, the MCPCB has good axial heat conduction but low in plane heat spreading. The thermosyphon PCB shows great promise since the axial and in planar thermal resistances seem to be quite low and heat can be spread in plane and out to the external heat sink in a highly effective manner. The Researchers of [1] have meticulously selected the materials for the prototype considering different aspects such as performance, compatibility, reliability and cost. The envelope for the thermosyphon PCB was chosen to be FR4 because of its low cost and easy availability. The other part of the envelope was made of oxygen free copper. The working fluids were Novec 7200 and 72DE since the latent heat, vapor pressure, surface tension properties were most suitable and compatible with other materials in the system. Permeation tests indicated that it is best to apply a copper coating on the FR-4 to provide the hermetic sealing necessary. The experiments also included adding wick structures to the evaporator section of the thermosyphon to enhance the boiling heat transfer rates.

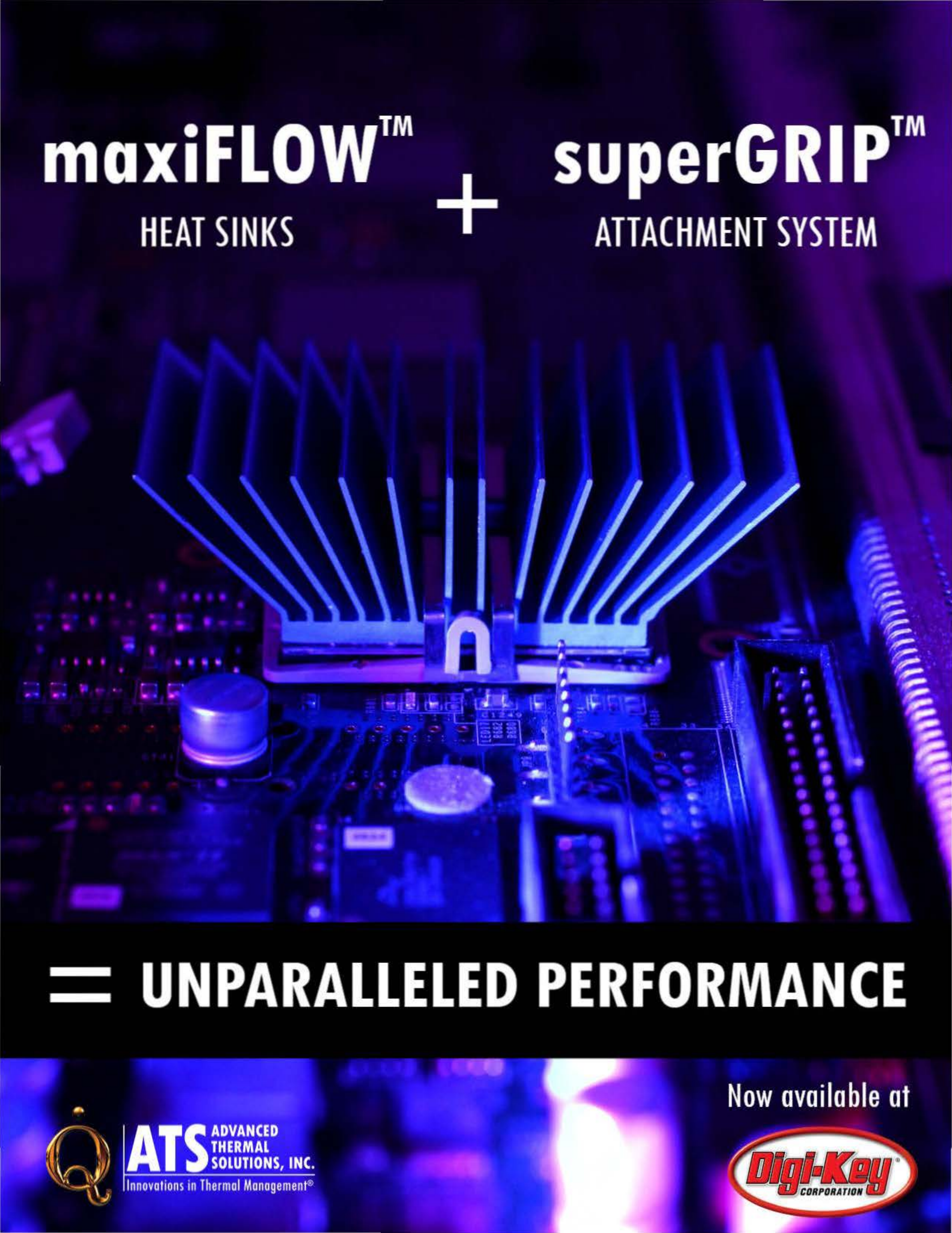
In conclusion, this appears to be a very promising technology aimed at reducing the planar thermal resistance of the PCB in high brightness LED applications. The improvement seen in CFD simulations was over 86% when compared to a traditional FR4 and 50% when compared to a Metal clad PCB. It is to be further seen how well this can be adapted to meet widespread implementation along with enhancing the design to make the performance of the system independent of gravity.

REFERENCES:

1. Bonner, R., Sharratt, S., and Ju, Y., “An Innovative Passive Cooling Method for High Performance Light-emitting Diodes “ 28th IEEE SEMI-THERM Symposium

2. http://www.electronics-cooling.com/2013/09/heat-pipe-integration-strategies-for-led-applications/

3. Wang, N., Hsu, A., Lim, A., Tan, J., Lin, C., Ru, H., Jiang, T., and Liao, D., “High Brightness LED Assembly using DPC substrate and SuperMCPCB”, IEEE 4th International Microsystem Packaging Assembly and Circuits Technology Conference IMPACT, 2009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