

*Crazy Idea:
Let's Make
Circuit Boards
out of FR-4!*



Testing the Performance of PTH and Copper Pour in Lieu of Metal Core PCBs in LED Applications

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SUMMARY: In 2009, author Yash Sutariya consulted Clemens Lasance, a thermal management guru, who began teaching the ways of the (thermal) force. Now, Yash is curious: Are brand-name thermal dielectrics on metal core printed circuit boards more effective than traditional FR-4 PCBs with Cu-plated vias?

“Life can be much broader once you discover one simple fact: Everything around you that you call life was made up by people that were no smarter than you and you can change it.” – Steve Jobs

Like the rest of the industry, I was swept up by the high-powered marketing campaigns promoting the performance benefits of cutting-edge dielectrics for LED PCBs. Not to mention I thought it was kind of cool making a PCB from a sheet of metal. Appealing to total cost of ownership, the wave informed us that the dielectric’s reliability performance justified the higher (purchase) cost. The wave had seemingly

short-circuited that part of my brain responsible for basic physics. As a result, when the current bragged about a thermal conductivity of 2-3 W/m K, I was inhibited from realizing that this was less than 1/100 that of copper’s thermal conductivity (400 W/m K).

In 2009, I consulted a thermal management guru who began teaching me the ways of the (thermal) force. Now, like Sid the Science Kid, I just have to know: Are brand-name thermal dielectrics on metal core printed circuit boards (MCPCBs) more effective than traditional FR-4 PCBs with Cu-plated vias?

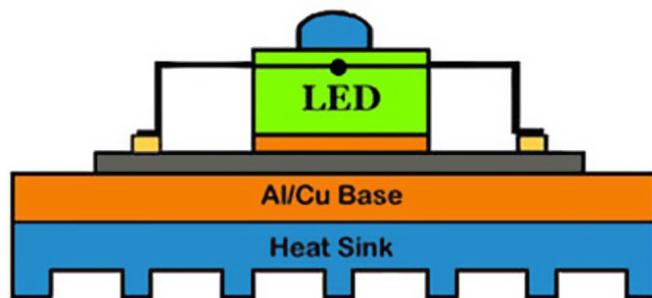


Figure 1: MCPCBs for LEDs.

PCBs for LED Thermal Management: The Basic Mechanism

The mechanism by which a thermally conductive PCB material works is fairly simple. The base of the LED component is soldered to a center pad of the component footprint. This center pad is not electrically connected to any of the other features. Its sole purpose is to provide a conduit for heat to be drawn away from the LED, increasing the light output as well as life of the product. MCPCBs in their simplest form consist of a circuit layer, a thermally conductive dielectric layer, and a metal substrate (most commonly aluminum). Once the PCB is assembled it is typically mounted to a heatsink with a thermal interface material (TIM).

PCBs for LED Thermal Management: The Basic Problems

MCPCB materials have numerous issues associated with them. First and foremost is the lack of an industry specification. As our past webinars have discussed, this results in a wide array of potential issues to the designer—primarily incorrect specifications that leave the end customer open to failures. Further, the MCPCB material can run up to 10 times the cost of standard FR-4, eroding the full potential savings of moving from incandescent to LED lighting.

This is where the lightning bolt struck me: By drilling and plating multiple vias into the heatsink pad of the LED component footprint and using traditional FR-4 two-layer plated-through-hole technology, could I create a PCB that rivals the thermal performance of metal-clad materials that cost up to 10 times that of standard FR-4 materials?

Being a novice in thermal calculations, I called on my trusted advisor, Clemens Lasance, who is principal scientist emeritus at Philips Research. A good portion of his career was dedicated to solving the challenge of thermal management electronic parts and systems. From the very beginning, Clemens was skeptical of vendors' claims pertaining to thermal conductivity requirements for the MCPCB in relation to thermal performance. In fact, he claimed that the MCPCB is the last element to attack in a chain that includes TIMs, heat sinks, convections, and the LED itself.

His reply was quick and simple:

When heat spreading is at stake, analytical solutions and approximate equations can only be used in limited cases where the designer is dealing with one- or two-layer problems with one-sided heat transfer and one source. Fortunately, many practical cases fall into this category, such as an FR-4 board with a copper top layer or metal core PCBs with a dielectric and a metal layer. For all other situations—for example when dealing with double-sided heat transfer, or multiple sources, or more than two layers, or when vias are applied, or when layers consist of more than one material, or for which the boundary conditions cannot be considered uniform—the problem becomes intractable from an approximate analytical point of view and we have to rely on computer codes.

It should be stressed that using analytical solutions, including the 1D series resistance network, has its main merits in getting insight, hence is second-to-none from an educational point of view. However, when accuracy is at stake in the final design stages, the recommended approach for solving real-life problems is in using a 3D conduction solver.

In principle, all finite volume/finite element, etc., codes can be used that solve the 3D heat diffusion equation. In practice, only those user-friendly codes are recommended that enable a designer to get results in a couple of hours or so. Some popular CFD codes dedicated to thermal management of electronic systems (FloTHERM, 6SigmaET, Icepak) used in conduction-only mode are examples of such a code.

For a fair comparison between an FR-4 board with copper layers at both sides provided with vias and an MCPCB board there is no other way than to use a 3D conduction solver. Of course experiments also can do the job, but to explore a range of parameters such as interface materials, heat sinks, convection modes, a choice of vias, copper layer thickness etc., the time gained by using numerical simulations is substantial. Estimated order of magnitude: One day for numerical simulation; one month to prepare and perform the tests. [1, 2]

Okay, so now we know we're on the right track. I asked Clemens to break out the Cray-

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ola 64-pack and draw me a picture so I could understand the concept. He did better: He created a 50,000-cell numerical model to analyze the various constructions I was discussing with him. The explanations behind these formulae and units of measurements can be found in Clemens' paper "Two-Layer Heat Spreading Revisited," presented at SemiTherm, March 2012, in San Jose, California [3].

We suggested comparing the following constructions:

- MCPCB;
- One-layer FR-4; and
- Two-layer FR-4 with vias under LED heatsink/slug.

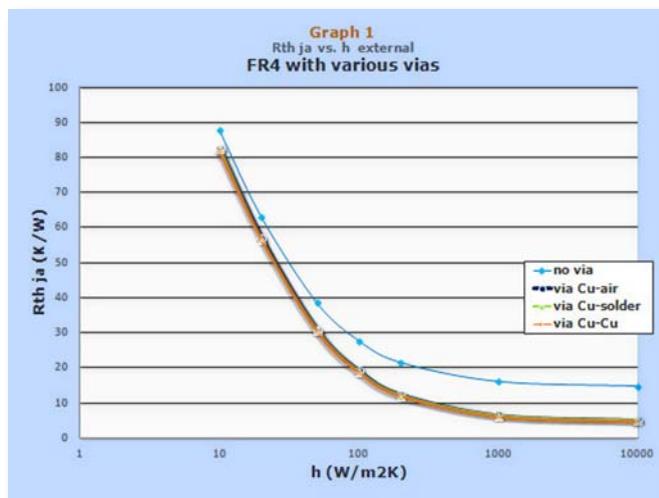
The basic assumptions used in the modeling were:

- LED with slug. The thermal resistance of the slug is orders of magnitude smaller than the one of the leads; hence, all power is delivered thru the slug.
- The LED is not modeled except for the slug; hence, all thermal resistances are from slug to ambient.
- All circular entities (slug, vias) are represented by squares with the same effective area.
- The heat sink is represented by a base connected to the PCB via a TIM; the fins are represented by an effective external heat transfer coefficient.
- Area allocated to a single LED is 25*25 mm.
- External h: h=10 W/m²K means free convection, no heat sink. h=100 means heat sink with area extension of factor of 10. h=1,000 is forced convection and h=10,000 liquid cooling.

We first wanted to compare the FR-4 constructions. In addition to the standard plated through vias, we thought to model vias that are filled with solder, as well as vias that are pure copper filled for comparison purposes.

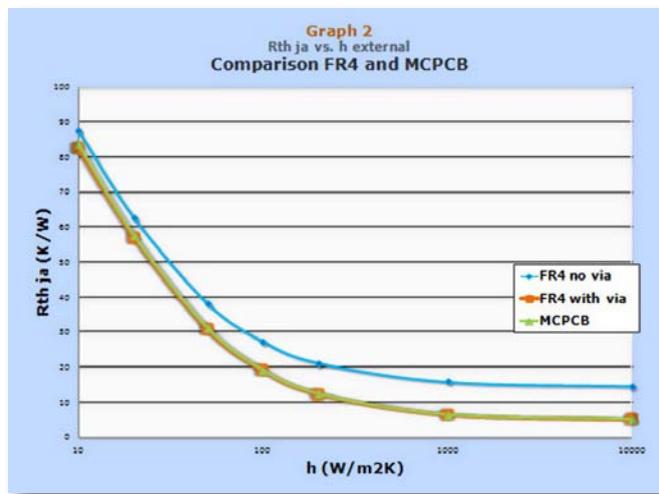
Author's Note: Clemens made his comments in regard to the following graphs:

The following graphs are based upon an analysis using FloTHERM in conduction-only mode (hence not solving the Navier-Stokes equations), applying quarter symmetry to a model consisting of both layouts with the LED slug as the power source and an heat sink base of 2 mm coupled with an interface material to the PCB in question.



Conclusion

Almost no difference can be found in the thermal performance of a standard via versus vias filled with solder or copper. This makes sense considering the very high thermal conductivity of copper. There is, however, a huge difference between an FR-4 board that has no vias and one that has plated through vias. Knowing this baseline data, we then plotted the thermal performance of the FR-4 boards against that of a traditional MCPCB that has a thermal resistance of approximately 0.09°C in²/W.



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Conclusion

Almost no difference can be found in the thermal performance of a PTH FR-4 board and a MCP-CB across a wide range of convection methods (h).

For years we have been pushing the idea that plated vias having >100x the thermal conductivity of thermally conductive dielectrics should be a viable alternative. We now have mathematical proof of concept.

FR-4 Thermal Vias Versus Thermally Dielectric MCPCBs: An Empirical Study

Now that we are armed with the confidence of having our theory proven correct via formulae, it made sense to run out and purchase a thermal imaging unit and create LED PCB test vehicles.

The following test vehicles were created:

- Aluminum core with copper pour;
- Aluminum core without copper pour;
- Two-layer copper pour (both sides);
- Two-layer copper pour (bottom);
- One-layer copper pour; and
- One-layer no copper pour.

The copper pours are comprised of 1-inch square areas of solid copper pour. Figures 2 and 3 are screen shots of both examples.

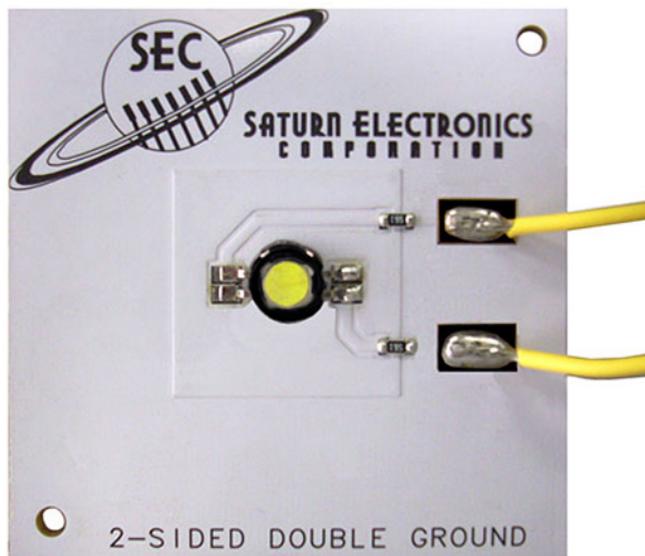


Figure 4: Test vehicle.

For the two-layer designs we duplicated the 1-inch top surface copper pour on the bottom layer. The intent was to have the heat from the LED base travel through the vias, and then spread across the bottom copper pour.

After allowing a one-hour burn-in to reach normal operating temperature, we took thermal images from a top vantage point of each LED test vehicle. The thermal imager also allows us to take temperature readings from the hottest

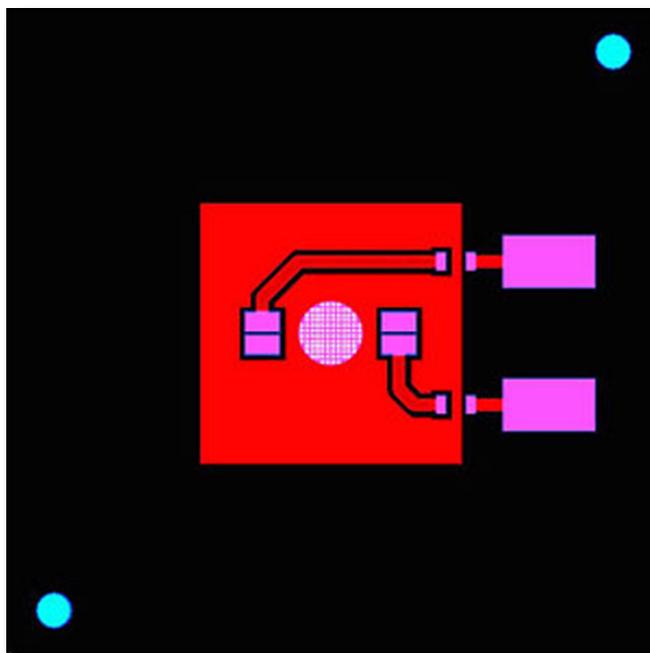


Figure 2: LED PCB with copper pour.

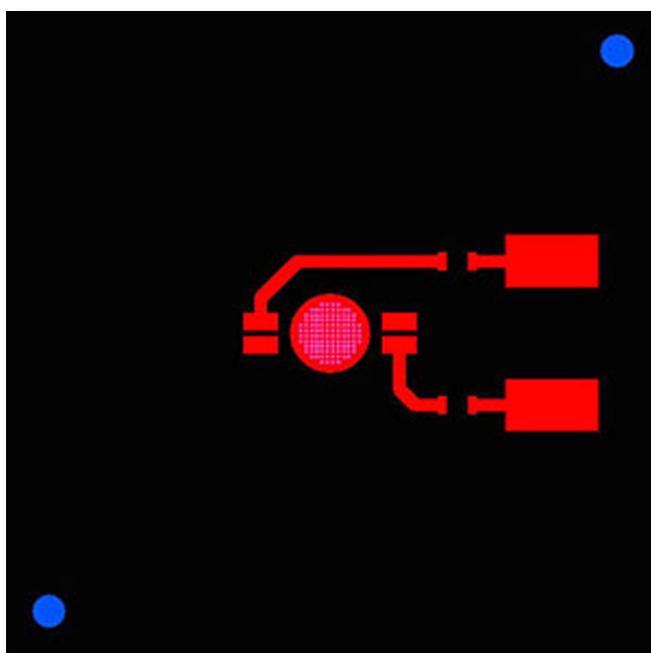


Figure 3: LED PCB without copper pour.

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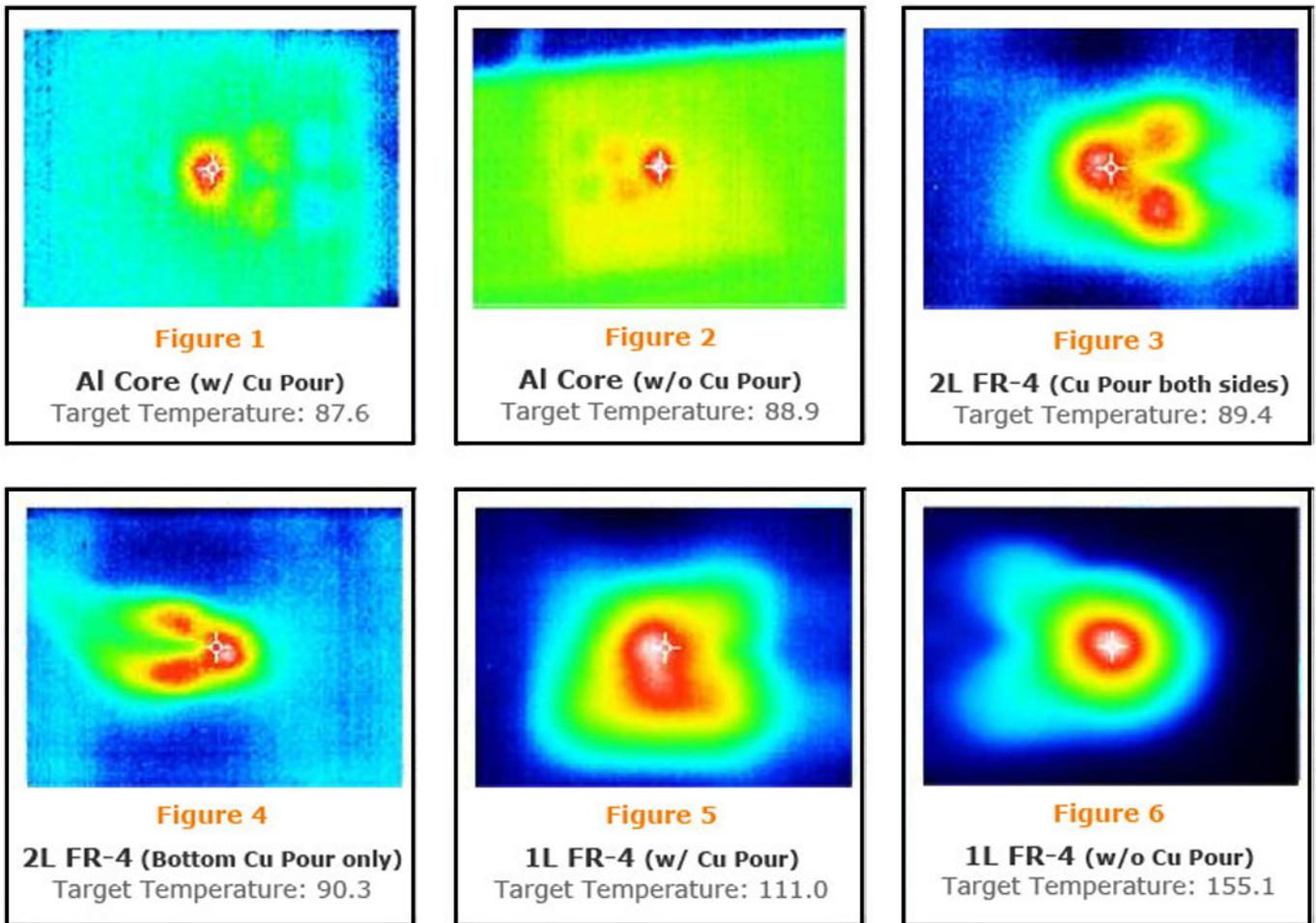
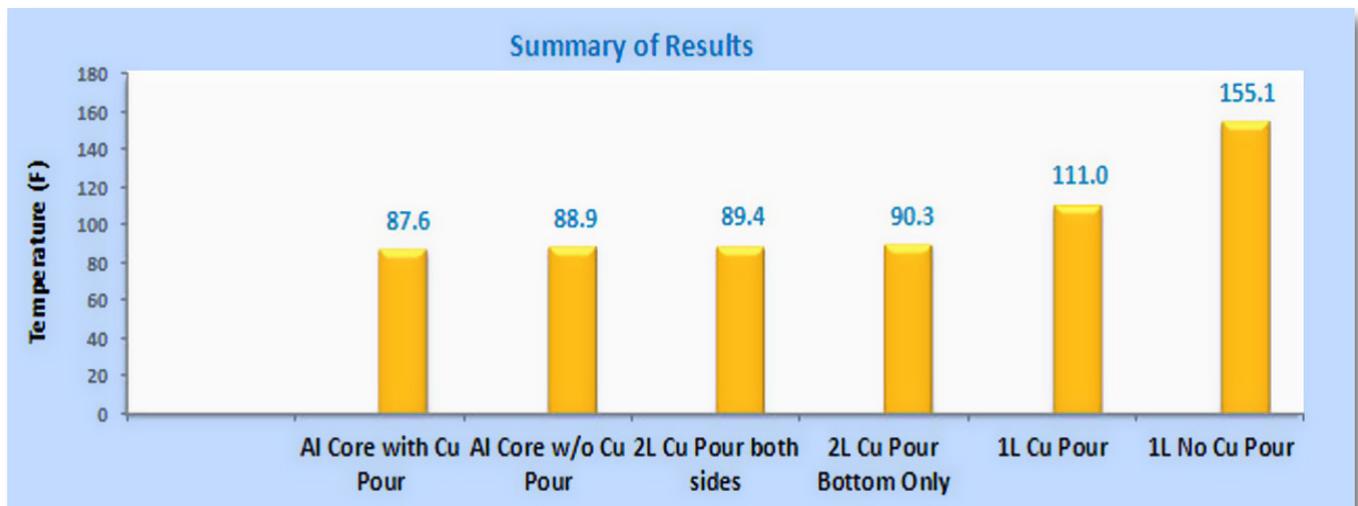


Figure 5: PCB thermal images from test vehicles.

point, namely the LED itself. The theory is that the heat measured from the top side is heat that has not been conveyed to the heatsink via the

thermally conductive dielectric (in the case of the MCPCB) or the PTH (in the case of the two-layer FR-4 boards) (Figure 5).



Graph 3: Graphical summary.

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Graphical Summary

The values in the chart represent surface temperature measurements only. However, it is more critical to calculate the temperature rise from ambient to glean the true performance of the thermal stackup, as shown in Graph 4.

FR-4 Thermal Vias Versus Thermally Dielectric MCPCBs:

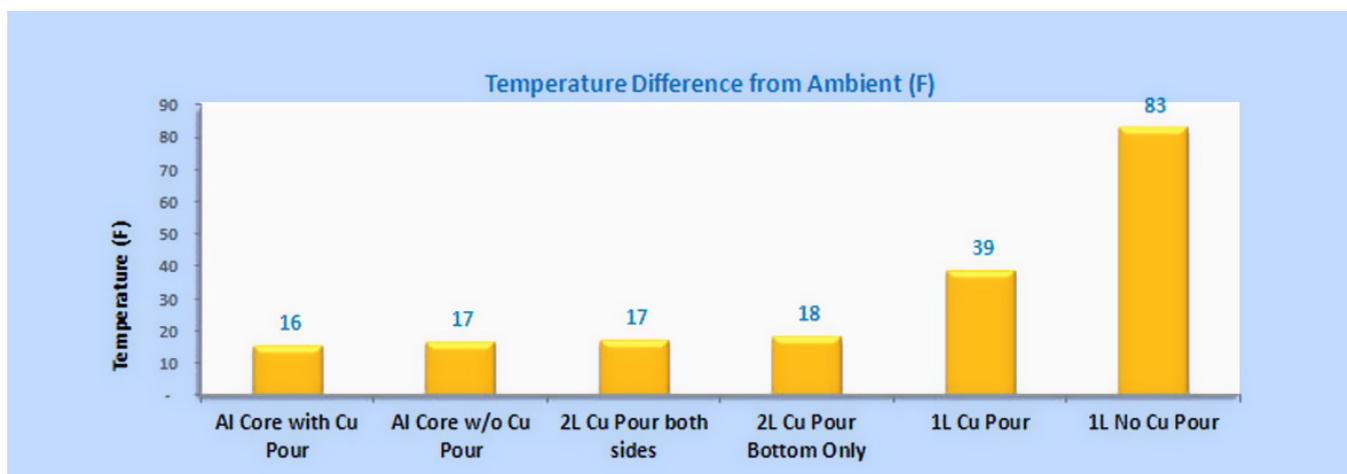
A (Cost) Benefit Calculation

When considering alternative solutions, it's always important to know what exactly will be the benefit. For the bean counters, it boils

down to the money saved. If we can assume that a particular design will perform the same between an MCPCB design and a plated via FR-4, can I save enough from a cost standpoint to compensate for additional testing and UL-related costs associated with converting my product over? Let's see (Graph 5).

Conclusion

Our test results demonstrate that FR-4 PCBs with Cu-plated vias achieve thermal transfer roughly equivalent to that of metal core PCBs with thermally-conductive material. Please note



Graph 4

CHARACTERISTIC	MCPCB	2L FR-4 PTH
Size	10.82" x 1.79"	10.82" x 1.79"
No. on 18"x24" Panel	18	18
Final Finish	SN100CL	SN100CL
EAU	25,000	25,000
Piece Price	\$6.37	\$2.65
Annualized Spend	\$159,173	\$66,322
Percent Difference		-58%
Annualized Savings		\$92,851

Graph 5: *Values will not calculate exactly due to rounding in the piece price.

that the results are specifically for this set of constraints including number of vias, LED type, and choice of MCPCB. Any designer wishing to convert their MCPCB design to use FR-4 with plated vias should not only contact a thermal management consultant for part-specific calculations, but also perform physical tests as we have done here. Should you need, Clemens Lasance can be contacted at lasance@onsnet.nu.

From a cost standpoint, the potential savings are substantial. The raw material savings alone more than compensate for the added processing steps required to create a two-layer plated through PCB. Further, it is difficult to find a supplier that is UL certified to a particular MCPCB material; conversely, using FR-4 technology allows the end user to add a great deal of competition to the supply base...as most PCB fabricators are already UL-certified to use FR-4 materials. **SMT**

References

1. Lasance, Clemens, "Heat spreading: not a trivial problem," *Electronics Cooling*, Vol. 14, pp. 24-30, May, 2008.

2. Lasance Clemens, "How to Estimate Heat Spreading Effects in Practice," *Journal of Electronics Packaging*, 132, 031004, 2010.

3. Lasance Clemens, "Two-layer heat spreading revisited," *Proceedings, SEMITHERM*, March 28, 2012, San Jose, California.

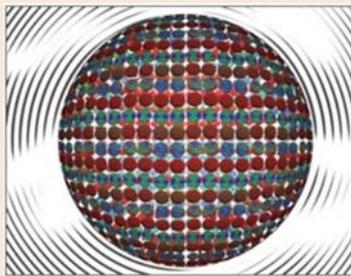


Yash Sutariya is vice president of Corporate Strategy at Saturn Electronics Corporation (SEC) and owner/president of Saturn Flex Systems, Inc. Since joining the team, SEC has successfully navigated from a low-mix, high-volume automotive supplier to a high-mix, medium- to high-volume diversified supplier. As a result of the company's transformation, manufacturing capabilities now range from quick-turn prototypes to scheduled volume production while attending a broad cross-section of industries to include industrial controls, telecommunications, aerospace and power supply industries.

Liquid Crystal Behavior Portends New Materials

Liquid crystals, the state of matter that makes possible the flat screen technology now commonly used in televisions and computers, may have new technological tricks in store. An international team of researchers led by University of Wisconsin-Madison Professor of Chemical and Biological Engineering Juan J. de Pablo reports the results of a computational study that shows liquid crystals, manipulated at the smallest scale, can unexpectedly induce the molecules they interact with to self-organize in ways that could lead to entirely new classes of materials with new properties.

Liquid crystals exhibit the order of a solid crystal but flow like a liquid. Used in combination with polarizers, optical filters and electric fields, liquid crystals underlie the pixels that



make sharp pictures on thin computer or television displays. Liquid crystal displays alone are a multi-billion dollar industry.

The new study modeled the behavior of thousands of rod-shaped liquid crystal molecules packed into nano-sized liquid droplets. It showed that the confined molecules self organize as the droplets are cooled. "At elevated temperatures, the droplets are disordered and the liquid is isotropic," de Pablo explains. "As you cool them down, they become ordered and form a liquid crystal phase. The liquid crystallinity within the droplets, surprisingly, induces water and other molecules at the interface of the droplets, known as surfactants, to organize into ordered nanodomains. This is a behavior that was not known."

In the absence of a liquid crystal, the molecules at the interface of the droplet adopt a homogeneous distribution. In the presence of a liquid crystal, however, they form an ordered nanostructure.