Electrical and Electronic Engineering 2012, 2(5): 303-308
DOI: 10.5923/j.eee.20120205.10

For the Journal "Electrical and Electronic Engineering", SAPUB Design of PCB for Power LEDs – Thermal Investigations

Petko Mashkov*, Berkant Gyoch, Stanislav Penchev, Hristo Beloev

8 Studentska str., University of Ruse, Ruse, 7017, Bulgaria

Abstract Investigations deal with development of cost effective thermal management for power LEDs. The technique involves usage of FR4 based PCBs which cost less, but have greater thermal resistance than metal core printed circuit boards (MCPCB). The use of copper pins underneath LED thermal pad is a method to dissipate heat through an FR4 PCB into an appropriate heat sink. Temperature regimes of operation of power XLamps LEDs mounted on MCPCBs and on the PCBs with copper pin are experimentally tested at various ambient conditions (air temperatures from 20℃ to 45℃) and different current values through LEDs – up to 600 mA. Infrared thermography for evaluation of temperature distribution on LEDs and heat sink is used. Thermal management investigations show that the developed design of FR4 PCB is successful and possess a lot of advantages.

Keywords Power Leds, Leds' Thermal Management

1. Introduction

Power LEDs possess a lot of advantages in comparison to other light sources. Luminaire efficacy of LEDs is better than efficacy of CFL (Compact Fluorescent Lamps) more than two times; LEDs' lifetime is five to fifty times longer than CFL's lifetime before requiring maintenance, there's no mercury, less power – plant pollution, less handful waste. But realizing advantages of LED luminaire demands precise thermal management calculations and investigations. It is well known that during operation of LEDs about 85% of electric power is turned into a heat in the LED chip and one of the most critical design parameters in LED illumination systems is the system's ability to draw heat away from the LED junction[1 – 3]. High operating temperatures at the LED junction adversely affect the performance of LEDs, resulting in decreased light output and lifetime.

The parameters which influence strongly on the junction temperature are: ambient temperature of the LED's immediate surroundings; power dissipated by the LED and thermal path between the LED junction and surroundings. The designer can not influence on the ambient temperature; the LED's power depends on the desirable luminous flux of one LED and in practice the most important task for realization all benefits of LED luminaire is proper thermal management of lighting equipment. Proper thermal management has to be considered in all its aspects. On one hand thermal resistance between solder point and immediate surroundings must be as low as it is possible; on the other hand assembling of LEDs onto the heat sink has to be easy, with few manual operations and cost effective.

The purpose of the investigations is designing a low-cost printed circuit board (PCB) layout which optimizes the transfer of heat from the LED.

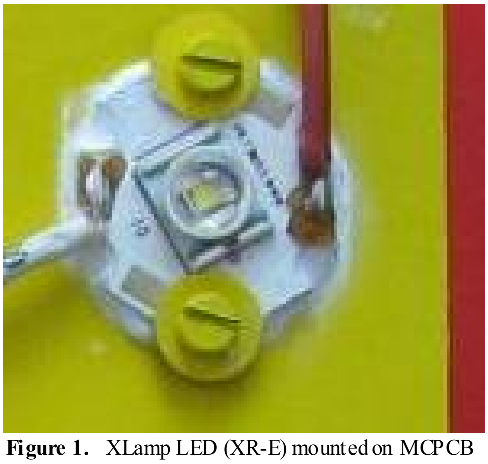

Figure 1. XLamp LED (XR-E) mounted on MCPCB

During investigations non contact measurements by infrared camera are used. The developed method[4, 5] gives a lot of advantages and allows evaluating temperature distribution easily and quickly on all LEDs in the light equipment (T_{sp}); on the PCBs' surfaces and on the whole areas of the heat sink. It allows calculating real thermal

* Corresponding author:
pmashkov@uni-ruse.bg (Petko Mashkov)
Published online at http://journal.sapub.org/eee

resistances of parts of light equipment at different orientations and operating conditions.

2. Problem Statement

Light equipment is designed on the base of LEDs XLamp XR – E White, CREE Inc., with light output 100 lm at 350 mA. At unconditioned spaces maximum ambient temperatures can reach 45℃ and proper heat sink must be chosen.

During operation heat flows from junction of the LED via solder point, PCB to the heat sink by way of conduction. The heat sink diffuses heat to the ambient surroundings mostly by convection[1].

Thermal resistance between junction of LED and ambient is a sum of thermal resistances:

- from the junction to the solder point ($R_{th\ j\text{-}sp}$);
- from the solder point to the heat sink ($R_{th\ sp\text{-}h}$);
- from the heat sink to ambient ($R_{th\ h\text{-}a}$)[1]:

$$R_{th\ j\text{-}a} = R_{th\ j\text{-}sp} + R_{th\ sp\text{-}h} + R_{th\ h\text{-}a}. \qquad (1)$$

Thermal management's calculations for lighting equipment in accordance to thermal resistance model for 12 XLamp LEDs are made (Fig. 2)[1].

In accordance to life time predictions[2, 3, 6-19] if during operation LEDs' junction temperatures T_j are kept below 80℃(or below 70℃) life time of the light equipment will be over 50 000 (70 000) hours.

Using this model the value of thermal resistance from heat sink to ambient is calculated and a proper heat sink with thermal resistance 0.9℃/W is chosen[4].

When used LEDs are mounted on MCPCB (Fig.1) our previous investigations[4] show good results concerning temperature distribution on the heat sink and LEDs' thermal regimes of operation.

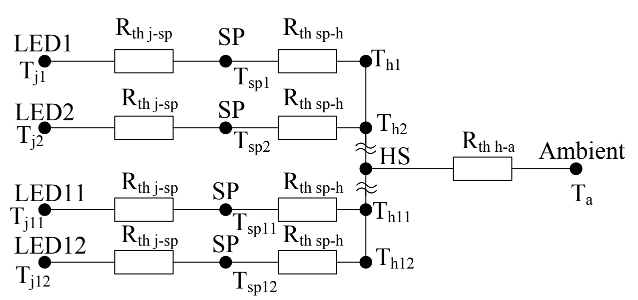

Figure 2. Thermal resistance model for 12 XLamps LEDs. $R_{th\ j\text{-}sp}$- thermal resistance from junction to solder point; $R_{th\ sp\text{-}h}$- thermal resistance from solder point to heat sink; $R_{th\ h\text{-}a}$- thermal resistance from heat sink to ambient

Usage of MCPCB is good for thermal management but has a lot of disadvantages. It demands many operations – soldering, boring holes, threading, screwing bolts. Thermal resistance of MCPCB is low – $R_{th\ sp\text{-}h}$ = 1℃/W[1] but assembling of MCPCB onto the heat sink isn't with good manufacturability.

A technique for designing a low-cost PCB layout which optimizes the transfer of heat from the LED is proposed[2]. The technique involves the use of FR4 based PCBs which cost less, but they have greater thermal resistance than metal core printed circuit boards (MCPCB) – Fig. 3 and Fig. 4. Usage of metal-lined holes or vias underneath LED thermal pads is a method to dissipate heat through an FR4 PCB and into an appropriate heat sink. All XLamp LED packages have an electrically isolated thermal pad. The pad provides an effective channel for heat transfer and optimizes thermal resistance from the LED chip junction to the thermal pad. The pad is electrically isolated from either the anode or cathode of the LED and can be soldered or attached directly to grounded elements on the board or heat sink system[2].

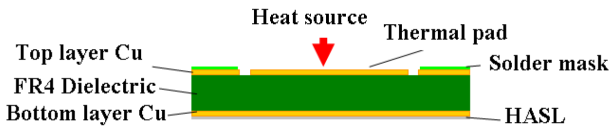

Figure 3. FR4 cross-sectional geometry. HASL - Hot Air Solder Level

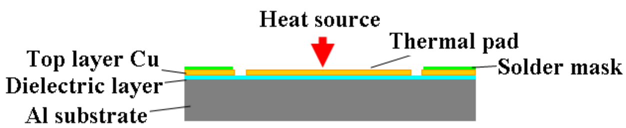

Figure 4. MCPCB cross-sectional geometry

Dimensions of recommended solder pad for XLamp XR family LEDs are shown in Fig.5.

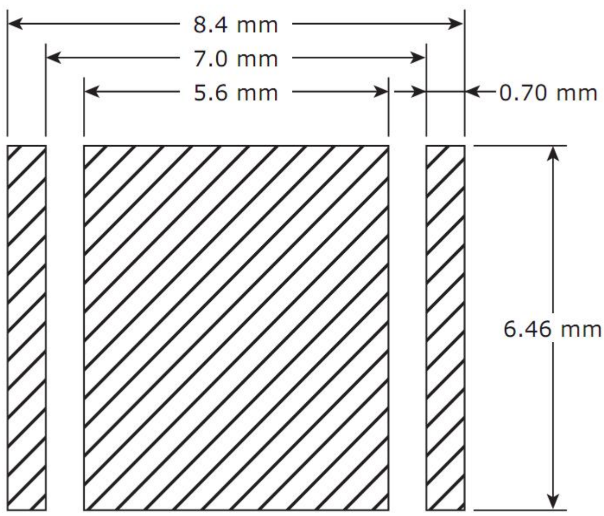

Figure 5. Recommended solder pad for XLamp XR family LEDs

Developed thermal performance of FR4 PCB includes boring the PCB in the center of thermal pad and usage copper pins underneath LEDs, Fig. 6. Two sizes pins are used - with 6 mm^2 cross section (diameter 2.76 mm) and 10 mm^2 cross section (diameter 3.57 mm).

Soldering of copper pins and LEDs to the PCB is simultaneous – in one soldering cycle. It is well known that thermal conductivity of copper is more than two times better than other materials and this design of PCB performance should ensure low thermal resistance between solder point of LED and heat sink.

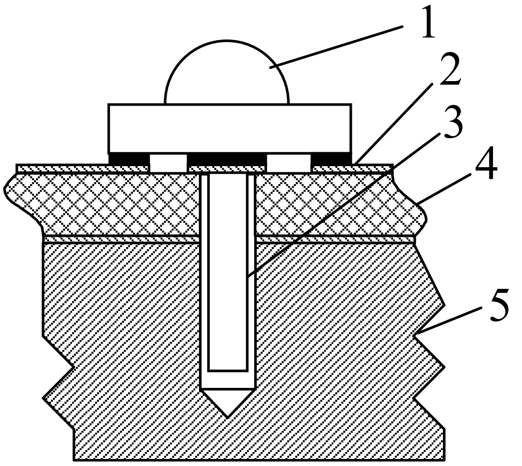

Figure 6. LED soldered on FR4 PCB with copper pin; 1 – LED; 2 – copper layer; 3 – copper pin; 4 – FR4 PCB; 5 – heat sink

To achieve reliable results concerning thermal resistance values of this PCB performance, an experimental approach is chosen.

Light equipment with LEDs on MCPCBs (Fig.1), previously experimentally tested at different operating conditions is used[4]. Temperature regimes of operation and temperature distributions on the heat sink for all LEDs are investigated[4]. LEDs are connected in series and they operate practically at the same regimes and temperature conditions. Distances between LEDs are 26/30 mm. Some of LEDs are unsoldered from MCPCBs and are soldered on FR4 PCBs with copper pins (Fig. 6). Then they are assembled at the previous places on the heat sink. It is important to draw attention to the fact that assembling of LEDs soldered on this type PCB to the heat sink is much easier compared to assembling of LEDs soldered on MCPCB to the heat sink. No threading and screwing bolts are needed. It is enough to bore a hole with proper diameter in the heat sink, to drip a drop thermoconductive epoxy resin in the hole and to put the copper pin into the hole. Assembling is easy, fast and cost effective.

3. Results

For evaluation of thermal effectiveness of PCB with copper pin (Fig. 6) a proved measuring method which is well described in[4, 5] is applied. LED panel is placed in experimental thermo chamber– Fig. 7. Infrared thermography is used for obtaining real temperatures of solder points of LEDs and temperature distribution on the heat sink's surface at different regimes of operation and different ambient conditions. Temperature distribution measurements are carried out using IR camera ThermaCam E300 – FLIR-Systems as it is described in[4, 5]. Results are verified by conventional measurements (by thermocouples mounted on two LEDs) in a manner recommended in[1].

Temperature in the thermal chamber is changed from 20℃ to 45℃ at intervals of 5℃. The value of current through LEDs is changed from 350 mA to 600 mA at intervals of 50mA. At each temperature and value of forward current when temperature equilibrium in the chamber is achieved, photos by IR camera are made. At each temperature the forward voltage drop on every LED is measured and real power consumption of every LED is calculated. Voltage measurements are carried out using multi meter MS-8050 with accuracy of 0.03%.

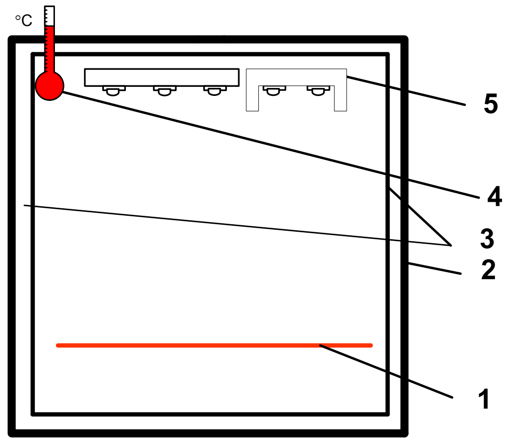

Figure 7. Cross-section view of experimental thermo chamber: 1- heater; 2- corpus of the chamber; 3- thermal insulation; 4- thermometer; 5 – LEDs panels

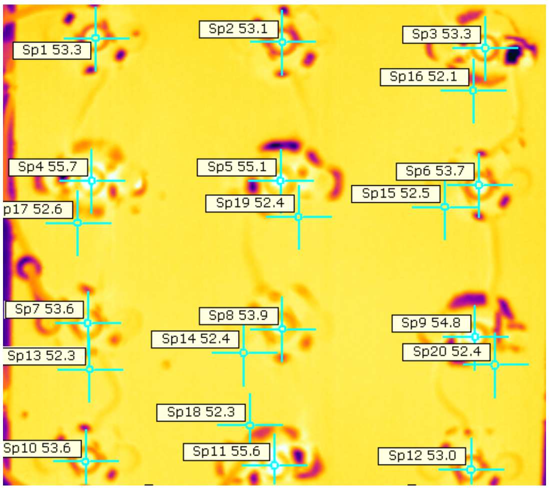

Figure 8. Photo of the LEDs' panel made by IR camera; $T_a = 40$℃ ; $I_F = 350$ mA – forward current through LEDs

During processing of IR photos, solder point temperature T_{sp} of each LED is determined and the surface temperature of the heat sink T_{hs} next to the same LED is measured (Fig. 8). Thermal resistance between solder point and heat sink can be calculated:

$$R_{th\ sp\text{-}h} = (T_{sp} - T_{hs}) / P_{LED}, \quad (2)$$

where

$$P_{LED} = I_F * U_F \quad (3)$$

is electric power of the LED; I_F and U_F are forward current and forward voltage drop of the LED.

For achieving reliable results more than 50 LEDs, (32 with copper pin 6 mm^2 and 24 with copper pin 10 mm^2) soldered on FR4 PCBs with copper pin are used during experimental investigations.

Some of basic results of the investigations concerning thermal resistance between solder point and heat sink are presented below.

Table 1a. Thermal resistance solder point – heat sink data for LEDs mounted on MCPCBs. Forward current $\mathbf{I_F}$ **= 500mA**; air temperature $\mathbf{T_{AIR}}$**=35℃**

LED on MCPCB			
LED	№ 6	№ 7	№ 8
U_F, V	3.074	3.052	3.036
P, W	1.537	1.526	1.518
T_{SP}, ℃	43.3	43.4	43.1
T_{HS}, ℃	41.1	41.3	41.2
$R_{Th\ sp\text{-}hs}$, ℃/W	1.43	1.38	1.25
$R_{Th\ sp\text{-}hs}$, (Average)	1.35℃/W		

Table 1b. Thermal resistance solder point – heat sink data for LEDs mounted on FR4 PCBs with copper **pin 6 mm^2 and pin 10 mm^2**. Forward current $\mathbf{I_F}$ **= 500mA**; air temperature $\mathbf{T_{AIR}}$**=35℃**

LED on FR4 PCB/Cu	pin 6 mm^2			pin 10 mm^2	
LED	№ 3	№ 4	№ 11	№ 5	№ 9
U_F, V	3.006	3.054	3.072	3.034	3.048
P, W	1.503	1.527	1.536	1.517	1.524
T_{SP}, ℃	42.8	44.7	44.9	43.8	43.9
T_{HS}, ℃	40.8	41.1	41.2	41.3	41.4
$R_{Th\ sp\text{-}hs}$, ℃/W	1.56	2.36	2.41	1.65	1.64
$R_{Th\ sp\text{-}hs}$, (Average)	2.11℃/W			1.65℃/W	

Table 2a. Thermal resistance solder point – heat sink data for LEDs mounted on MCPCBs. Forward current $\mathbf{I_F}$ **= 500mA**; air temperature $\mathbf{T_{AIR}}$**=40℃**

LED on MCPCB			
LED	№ 6	№ 7	№ 8
U_F, V	3.002	3.021	3.024
P, W	1.501	1.510	1.512
T_{SP}, ℃	53.7	53.6	53.9
T_{HS}, ℃	52.2	52.1	52.3
$R_{Th\ sp\text{-}hs}$, ℃/W	1.00	0.99	1.06
$R_{Th\ sp\text{-}hs}$, (Average)	1.02℃/W		

Table 2b. Thermal resistance solder point – heat sink data for LEDs mounted on FR4 PCBs with copper **pin 6 mm^2 and pin 10 mm^2**; Forward current $\mathbf{I_F}$ **= 500mA**; air temperature $\mathbf{T_{AIR}}$**=40℃**

LED on FR4 PCB/Cu	pin 6 mm^2			pin 10 mm^2	
LED	№ 3	№ 4	№ 11	№ 5	№ 9
U_F, V	3.046	3.034	3.052	3.032	3.022
P, W	1.523	1.517	1.526	1.516	1.511
T_{SP}, ℃	54.3	55.5	55.4	55.1	54.6
T_{HS}, ℃	52.1	52.6	52.3	52.4	52.4
$R_{Th\ sp\text{-}hs}$, ℃/W	1.44	1.91	2.03	1.78	1.46
$R_{Th\ sp\text{-}hs}$, (Average)	1.79℃/W			1.62℃/W	

Table 3a. Thermal resistance solder point – heat sink data for LEDs mounted on MCPCBs; Forward current $\mathbf{I_F}$ **= 600mA**; air temperature $\mathbf{T_{AIR}}$**=35℃**

LED on MCPCB			
LED	№ 6	№ 7	№ 8
U_F, V	3.053	3.032	3.047
P, W	1.832	1.819	1.828
T_{SP}, ℃	49.6	49.4	49.7
T_{HS}, ℃	47.5	47.6	47.8
$R_{Th\ sp\text{-}hs}$, ℃/W	1.15	0.99	1.04
$R_{Th\ sp\text{-}hs}$, (Average)	1.06℃/W		

Table 3b. Thermal resistance solder point – heat sink data for LEDs mounted on FR4 PCBs with copper **pin 6 mm^2 and pin 10 mm^2**; Forward current $\mathbf{I_F}$ **= 600mA**; air temperature $\mathbf{T_{AIR}}$**=35℃**

LED on FR4 PCB/Cu	pin 6 mm^2			pin 10 mm^2	
LED	№ 3	№ 4	№ 11	№ 5	№ 9
U_F, V	3.068	3.082	3.088	3.071	3.059
P, W	1.841	1.849	1.853	1.842	1.836
T_{SP}, ℃	49.4	51.2	51.1	50.2	50.0
T_{HS}, ℃	47.5	48.0	47.9	47.7	47.6
$R_{Th\ sp\text{-}hs}$, ℃/W	1.03	1.73	1.73	1.36	1.31
$R_{Th\ sp\text{-}hs}$, (Average)	1.50℃/W			1.34℃/W	

Table 4a. Thermal resistance solder point – heat sink data for LEDs mounted on MCPCBs; Forward current $\mathbf{I_F}$ **= 600mA**; air temperature $\mathbf{T_{AIR}}$**=40℃**

LED on MCPCB			
LED	№ 6	№ 7	№ 8
U_F, V	3.048	3.023	3.035
P, W	1.829	1.814	1.821
T_{SP}, ℃	53.7	53.6	53.9
T_{HS}, ℃	52.0	51.9	52.1
$R_{Th\ sp\text{-}hs}$, ℃/W	0.93	0.94	0.99
$R_{Th\ sp\text{-}hs}$, (Average)	0.95℃/W		

Table 4b. Thermal resistance solder point – heat sink data for LEDs mounted on FR4 PCBs with copper **pin 6 mm^2 and pin 10 mm^2**; Forward current $\mathbf{I_F}$ **= 600mA**; air temperature $\mathbf{T_{AIR}}$**=40℃**

LED on FR4 PCB/Cu	pin 6 mm^2			pin 10 mm^2	
LED	№ 3	№ 4	№ 11	№ 5	№ 9
U_F, V	3.055	3.063	3.068	3.061	3.048
P, W	1.833	1.838	1.841	1.836	1.829
T_{SP}, ℃	53.3	55.7	55.6	55.1	54.8
T_{HS}, ℃	51.1	52.9	52.9	52.8	52.3
$R_{Th\ sp\text{-}hs}$, ℃/W	1.20	1.52	1.47	1.25	1.26
$R_{Th\ sp\text{-}hs}$, (Average)	1.40℃/W			1.26℃/W	

Results presented in the tables and figures show thermal resistance of FR4 PCBs significantly greater than this of MCPCBs - formally over 40%. Practically measured temperature differences are below 2 ÷ 3 degrees; in some cases they are smaller than accuracy of measuring method. For evaluation of real thermal effectiveness of the developed design of FR4 PCBs series of experimental investigations are made. Solder point's temperatures T_{sp} dependences on temperatures of the ambient air T_a at different forward current values for LEDs on MCPCBs and for LEDs on FR4

PCBs are investigated. Some results are presented in Fig. 9.

At each value of solder points' temperatures T_{sp} the corresponding temperatures of the junction of the LEDs are calculated in accordance with:

$$T_j = T_{sp} + R_{th\ j\text{-}sp} * P_{LED}. \quad (4)$$

Some of results (for copper pins with 6 mm^2 cross section) are presented below – Fig. 10.

As it can be seen from the results this design of FR4 PCB with copper pin ensures good thermal resistance between solder point and heat sink. LEDs' junction temperature doesn't reach 80℃ even at 45℃ air temperature and 600 mA forward current. FR4 PCBs with bigger copper pins (10 mm^2 cross section) don't possess any advantages compared to these with 6 mm^2 copper pins. That's why in our following works only 6 mm^2 copper pins are used.

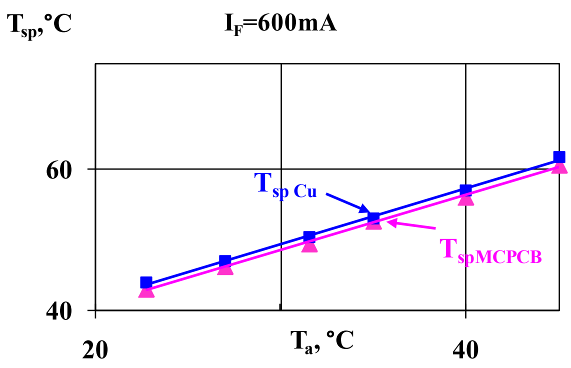

Figure 9. Solder point's temperature T_{sp} dependences on temperature of the ambient air T_a; I_F = 600 mA – forward current through LEDs. $T_{sp\text{-}Cu}$ – for LEDs on FR4 PCBs with 6 mm^2 copper pin (■); $T_{sp\text{-}MCPCB}$ – for LEDs on MCPCBs (▲)

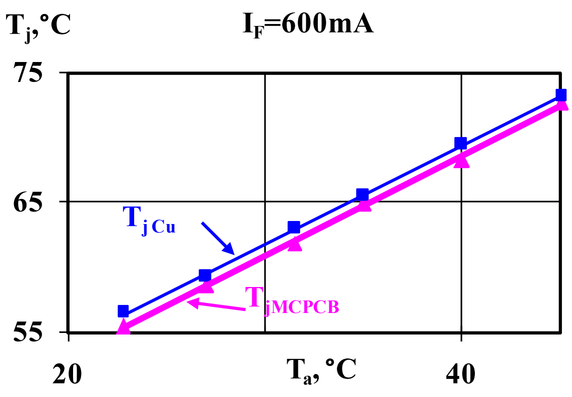

Figure 10. Junction temperature T_j dependences on temperature of the ambient air T_a; I_F = 600 mA – forward current through LEDs; $T_{j\text{-}Cu}$ – for LEDs on FR4 PCBs with 6 mm^2 copper pin (■); $T_{j\text{-}MCPCB}$ – for LEDs on MCPCBs (▲)

4. Conclusions

Design of low-cost FR4 printed circuit board (PCB) layout which optimizes the transfer of heat from LEDs to heat sink is proposed. Developed thermal performance of FR4 PCB includes usage of copper pins underneath LEDs' thermal pads. This design ensures low thermal resistance between LED's solder point and heat sink (like MCPCB) and gives possibility for realization easy, low cost, with few manual operations assembling of LEDs to the heat sink.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Education and Science of Bulgaria under Grant Projects VU-EES-301/2007, 12-FEEA-02.

REFERENCES

[1] XLamp LED Thermal management; www.cree.com/xlamp.

[2] Optimizing PCB Thermal Performance for Cree XLamp LEDs; www.cree.com/xlamp

[3] XLamp long – term lumen maintenance; www.cree.com/xlamp.

[4] Mashkov P., T. Pencheva, B. Gyoch. Temperature Measurement Methods for Power LEDs' Thermal Performance Investigations. Advanced Packaging Materials /MicroTech 2010 – Booking Form 1st – 2nd March 2010 – Moller Centre, Cambridge, England, pp. 68-73.

[5] Mashkov P., T. Pencheva, B. Gyoch. LEDs' operation optimizing for long term lumen maintenance. IEEE, Proc. of 33th International Spring Seminar on Electronics Technology - ISSE 2010, Warsow, Poland, May 12th – 16th 2010, D13pp. 1 – 6.

[6] Keppens A, W.R.Ryckaert, G.Deconinck, P.Hanselaer; High power light emitting diode junction temperature determination from current-voltage characteristics; Journal of Applied Physics 104, 093104, 2008.

[7] Weilguni M., J. Nicolics, R. Medek, M. Franz, G. Langer and F. Lutschounig. Characterization of the Thermal Impedance of High-Power LED Assembly based on Innovative Printed Circuit Board Technology, IEEE, Proc. of 33th International Spring Seminar on Electronics Technology - ISSE 2010, Warshaw, Poland, May 12th – 16th 2010, D14, pp. 1 - 6.

[8] Yang, L., Hu, J., Shin, M.W., Dynamic thermal analysis of high-power LEDs at pulse conditions, IEEE Electron Device Letters 29 (8), 2008, pp. 863-866.

[9] Lin, D.T.W., Huang, C.-N., Chang, C.-C., The optimization of the heat removal on the LED package Advanced Science Letters 4 (6-7), 2011, pp. 2301-2305.

[10] Guo, W., Jia, X., Yin, F., Cui, B., Gao, W., Liu, Y., Yan, W., Characteristics of high power LEDs at high and low temperature, Journal of Semiconductors 32 (4) , 2011,art. no. 044007.

[11] Horng, R.H., Chiang, C.C., Hsiao, H.Y., Zheng, X., Wuu, D.S., Lin, H.I., Improved thermal management of GaN/sapphire light-emitting diodes embedded in reflective heat spreaders, Applied Physics Letters 93 (11), 2008, art. no. 111907.

[12] Tian, X., Chen, W., Zhang, J., Thermal design for the high-power LED lamp, Journal of Semiconductors 32 (1) ,

2011, art. no. 014009.

[13] Hou, F., Yang, D., Zhang, G., Thermal analysis of LED lighting system with different fin heat sinks, Journal of Semiconductors 32 (1), 2011, art. no. 014006.

[14] Liu, S., Yang, J., Gan, Z., Luo, X., Structural optimization of a microjet based cooling system for high power LEDs, International Journal of Thermal Sciences 47 (8), 2008, pp. 1086-1095.

[15] Deng, Y., Liu, J., A liquid metal cooling system for the thermal management of high power LEDs, International Communications in Heat and Mass Transfer 37 (7), 2010, pp. 788-791.

[16] Yu, G., Zhu, X., Hu, S., Hao, W., Guo, T., Thermal simulation and optimization design on a high-power LED spot lamp, Optoelectronics Letters 7 (2), 2011, pp. 117-121.

[17] Christensen, A., Graham, S., Thermal effects in packaging high power light emitting diode arrays, Applied Thermal Engineering 29 (2-3), 2009, pp. 364-371.

[18] Yang, H., Bergmans, J.W.M., Schenk, T.C.W., Linnartz, J.-P.M.G., Rietman, R., An analytical model for the illuminance distribution of a power LED, Optics Express 16 (26), 2008, pp. 21641-21646.

[19] Huang, B.-J., Huang, H.-H., Chen, C.-W., Wu, M.-S., Development of high-power LED lighting luminaires using loop heat pipe, Journal of Light and Visual Environment 32 (2), 2008, pp. 148-155.