Numerical thermal analysis and optimization of multi-chip LED module using response surface methodology and genetic algorithm

Tang, Hong Yu; Ye, Huai Yu; Chen, Xian Ping; Qian, Cheng; Fan, Xue Jun; Zhang, Guo Qi

DOI
10.1109/ACCESS.2017.2737638

Publication date
2017

Document Version
Final published version

Published in
IEEE Access

Citation (APA)

Important note
To cite this publication, please use the final published version (if applicable). Please check the document version above.
Numerical Thermal Analysis and Optimization of Multi-Chip LED Module Using Response Surface Methodology and Genetic Algorithm

HONG-YU TANG\textsuperscript{1,2}, (Student Member, IEEE), HUAI-YU YE\textsuperscript{3}, (Member, IEEE), XIAN-PING CHEN\textsuperscript{3}, (Member, IEEE), CHENG QIAN\textsuperscript{2,4}, (Member, IEEE), XUE-JUN FAN\textsuperscript{5}, (Senior Member, IEEE), AND GUO-QI ZHANG\textsuperscript{1}, (Fellow, IEEE)

\textsuperscript{1}Electronic Components, Technology and Materials, Delft University of Technology, 2628 CD Delft, The Netherlands
\textsuperscript{2}Changzhou Institute of Technology Research for Solid State Lighting, Changzhou 213161, China
\textsuperscript{3}Key Laboratory of Optoelectronic Technology & Systems, Education Ministry of China, College of Opto-electronic Engineering, Chongqing University, Chongqing 400044, China
\textsuperscript{4}State Key Laboratory of Solid State Lighting, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
\textsuperscript{5}Department of Mechanical Engineering, Lamar University, Beaumont, TX 77710, USA

Corresponding authors: Huai-Yu Ye (h.ye@tudelft.nl) and Guoqi Zhang (g.q.zhang@tudelft.nl)

This work was supported in part by the Beijing Municipal Commission of Science and Technology, in part by the TUD China Research Institute, in part by the National High Technology Research and Development Program of China (863 Program) under Grant 2015AA033304, and in part by the International Science & Technology Cooperation Program of China under Grant 2015DFG62430.

\textbf{ABSTRACT} In this paper, the heat transfer performance of the multi-chip (MC) LED module is investigated numerically by using a general analytical solution. The configuration of the module is optimized with genetic algorithm (GA) combined with a response surface methodology. The space between chips, the thickness of the metal core printed circuit board (MCPCB), and the thickness of the base plate are considered as three optimal parameters, while the total thermal resistance ($R_{\text{tot}}$) is considered as a single objective function. After optimizing objectives with GA, the optimal design parameters of three types of MC LED modules are determined. The results show that the thickness of MCPCB has a stronger influence on the total thermal resistance than other parameters. In addition, the sensitivity analysis is performed based on the optimum data. It reveals that $R_{\text{tot}}$ increases with the increased thickness of MCPCB, and reduces as the space between chips increases. The effect of the thickness of base plate is far less than that of the thickness of MCPCB. After optimization, three types of MC LED modules obtain lower $T_j$ and $R_{\text{tot}}$. Moreover, the optimized modules can emit large luminous energy under high-power input conditions. Therefore, the optimization results are of great significance in the selection of configuration parameters to improve the performance of the MC LED module.

\textbf{INDEX TERMS} Multi-chip LED module, optimization, response surface methodology, genetic algorithm, thermal resistance.

\textbf{I. INTRODUCTION}

Light emitting diodes (LEDs) have been used as LCD back light sources, automotive and general lightings due to their low power consumption, highly directional light emission, fast response time, long lifetime and environmental protection [1]–[5]. To achieve more lumen and lower cost, LEDs have been packaged in multi-chip packaging modules and driven at high current density [6]–[8]. However, there is only about 20% of the input power is transformed into light in the LEDs, the remaining energy is converted to heat [9]–[11]. If such superheat cannot be removed effectively, high temperature and temperature gradient inside LEDs will not only generate significant stresses along the interfaces [12]–[14] but also accelerate light output degradation and even catastrophic failure [15]–[19]. Thus, thermal management is necessary for a multi-chip LED (MC LED) module to gain a reliable and good performance [20]–[22]. In general, most of the heat generated from LED chips conducts through heat spreader to substrate and finally transfers from heat sink to environment. There exists a large thermal resistance associated with the spreading of heat from a small heat sources to a much larger substrate base [23]. Besides,
LED module with vertical LED chip shows very high thermal resistance of $15 \sim 30 \, \text{°C/W}$ [24] due to the low thermal conductivities of substrate (0.3-3 W/mK for metal core printed circuit board (MCPCB) [25]–[27]). What’s more, the number of chips [28] and the layout of LED array [29] have significant effects on the overall illumination quality and thermal performance. Therefore, optimizing the layout of chips and the geometry of module are effective and important for enhancing the performance of MC LED module.

There are several approaches to improve the conductive thermal resistance, thermal spreading resistance, and convective thermal resistance of LED module for decreasing the total thermal resistance. To reduce conductive thermal resistance (also called one-dimensional thermal resistance ($R_{1D}$)), the thickness of solder [30], [31], board and dielectric layer [27] of LED module was optimized separately. Moreover, high thermal conductivity materials, such as carbon nanotube [32] and graphene-based nanocomposite [33], [34] were utilized to decrease $R_{1D}$. For optimizing the thermal spreading resistance, Cheng et al. [7] presented an analytical model for optimizing a uniform temperature profile of multi-chip LED package by changing the chips arrangement on the substrate. Yung et al. [29] addressed different placement configuration and different PCB materials to achieve lower LED temperature and higher luminous efficacy. What’s more, lots of studies focus on the optimum design of heat sink/heat spreader, which can largely reduce the convective thermal resistance of LED module [21], [35]. All of the above studies reveal that configuration optimization of LED modules is needed.

Indeed, design of experiment (DOE) and optimization algorithms have been successfully applied for the optimal design of LED module. Jeon et al. [36] optimized the hybrid LED package system based on micro machining technology and Taguchi method. Jeong et al. [27] presented geometric optimization in a LED module with aluminum nitride insulation plate by using Box–Behnken design method. In addition, many researchers have successfully optimized the plate-fin heat exchangers/heat sink with genetic algorithm (GA) and response surface methodology (RSM) by considering maximum the total rate of heat transfer and minimum the total annual cost with given constrained condition [37]–[39]. However, few of them optimize the MC LED module by systematically considering the layout of chips and the geometry of module.

In this paper, an effective general analytical solution proposed by Muzychka et al. [40] is used to calculate the heat source temperature and thermal resistance in MC LED module. The objective of present work is to study the effects of configuration parameters (space between the LED chips, thickness of MCPCB and base plate) on the heat dissipation performance of MC LED module. The optimization of the geometric parameters by the RSM and GA with the analytical solution are implemented. The thermal performance and luminous efficacy of the MC LED modules are compared before and after optimization.

## II. NUMERICAL ANALYSIS

### A. NUMERICAL METHOD

Muzychka et al. [40] have presented a general analytical solution for a thermal spreading resistance of eccentric heat sources on a rectangular flux channel. The planar rectangular heat source of dimensions $c$ and $d$ is located at the end of a compound heat flux channel. The channel of dimensions $a$ and $b$ consists of two layers having thicknesses $t_1$ and $t_2$ and thermal conductivities $k_1$ and $k_2$, respectively. The heat flux is cooled along the bottom surface with a uniform heat transfer coefficient $h$. The lateral boundaries of the heat flux channel are adiabatic. $Q$ is the total thermal flux from the heat source.

The solution is $\theta(x, y, z) = T(x, y, z) - T_f$, where $T(x, y, z)$ is the layer temperature, and $T_f$ is the heat sink temperature. It can be used to model any number of discrete heat sources on a heat sink. The temperature excess of each heat source can be computed using the following equation evaluated at the surface:

$$\theta_i(x, y, 0) = A_0 + \sum_{n=1}^{\infty} A_n^1 \cos(\lambda c + \frac{\pi n}{b}) \cos(\delta y)$$

$$+ \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \cos(\lambda c + \frac{\pi n}{b}) \cos(\delta y), \quad (1)$$

where $\theta_i$ is the temperature excess for each heat source by itself, $\lambda = \frac{m \pi}{a}$, $\delta = \frac{n \pi}{b}$; The final Fourier coefficients $A_m, A_n,$ and $A_{mn}$ are obtained by taking Fourier series expansions of boundary condition at the surface $z = 0$.

$$A_0 = \frac{Q}{ab} \left( \frac{t_1}{k_1} + \frac{1}{h} \right) \quad (2)$$

$$A_m = \frac{2Q}{abck_1} \left( \sin \left( \frac{2\lambda c + \pi m}{2}\right) \right) \frac{\sin \left( \frac{\lambda c}{2} - \frac{\pi m}{2}\right)}{\lambda c \sin \left( \frac{\lambda c}{2}\right) \sin \left( \frac{\pi m}{2}\right)} \Phi(\lambda c) \quad (3)$$

$$A_n = \frac{2Q}{abcdk_1} \left( \sin \left( \frac{2\lambda c + \pi m}{2}\right) \right) \frac{\sin \left( \frac{\lambda c}{2} - \frac{\pi m}{2}\right)}{\lambda c \sin \left( \frac{\lambda c}{2}\right) \sin \left( \frac{\pi m}{2}\right)} \Phi(\lambda c) \quad (4)$$

$$A_{mn} = \frac{16Q}{abcdk_{1b}} \left( \sin \left( \frac{\lambda c}{2}\right) \right) \cos \left( \frac{\pi m}{2}\right) \cos \left( \frac{\lambda c}{2}\right) \cos \left( \frac{\pi m}{2}\right) \sin \left( \frac{\lambda c}{2}\right) \sin \left( \frac{\pi m}{2}\right) \Phi(\lambda c) \quad (5)$$

For $N$ discrete heat sources, the surface temperature distribution is given by:

$$T(x, y, 0) - T_f = \sum_{i=1}^{N} \theta_i(x, y, 0) \quad (6)$$

In general, the total resistance is defined as:

$$R_{tot} = \frac{\bar{f}}{Q} = R_{1D} + R_S, \quad (7)$$

where $R_{1D}$ is the one-dimensional thermal resistance and $R_S$ is the thermal spreading resistance. The thermal spreading resistance of the $i$th heat source is expressed as:

$$R_{s,i} = \frac{T_f - T_f}{Q} - R_{1D} = \frac{\sum_{i=1}^{N} \theta_i}{Q} - \left( \frac{t_1}{k_1} + \frac{t_2}{k_2} + \frac{1}{h} \right) \quad (8)$$
FIGURE 1. Configuration of MC LED module mounted on heat sink (left) and its simplified model (right).

The temperature distribution on the surface of base plate is computed based on the general solution. This paper calculates the maximum thermal resistance in the rectangular flux channels, which is the thermal resistance of heat sources with the highest junction temperature in the MC LED module.

B. MODELING AND NUMERICAL RESULTS

In a LED module, LED chips (heat sources) are bonded on MCPCB (rectangular channel) and mounted on a heat sink (see Fig. 1). The complicated structure of module is simplified to satisfy the condition of the solution presented by Muzychka et al., which consists of a base plate, an MCPCB, and LED chips. LED chips are simplified into squares, whose sizes are 1 mm × 1 mm. The geometric conditions and thermal conductivities of the LED module are listed in Table 1.

An equivalent convection coefficient to represent both the heat transfer in the fin surface and the plate surface is applied on the bottom of base plate, which is 1000 W/m²K here. Since most of heat is dissipated by conduction, heat radiation is neglected here [41]. As shown in Fig. 1, uniform heat flux boundary condition is applied to the top of the chips, while constant temperature condition is applied to the bottom surface of base plate. The heat input \( Q \) calculated by subtracting the light output from the electric power, is 0.28 W. \( T_f \) is set as 25 °C. A MATLAB program is built to calculate the above equations (1)-(6) and draw the isothermal chart.

One MC LED module, composed of seven LED chips, one MCPCB, and one base plate, is analyzed as shown in Fig. 2. The space between the inner and outer chips is \( x_1 \). \( T_j \) is the mean junction temperature of the module. Obviously, the \( T_j \) drops gradually with increasing \( x_1 \). There is no significant change on the edge temperatures of MCPCB (\( T_{E,c} \)) because the total thermal power is constant in each module. Likewise, the thermal resistance (\( R_{tot} \)) of module decreases with increasing \( x_1 \). The results show that the space of the chips has considerable influence on \( R_{tot} \) and thermal uniformity of MC LED module. \( R_{tot} \) is decreased by nearly 14.5% when the layout changes from the smallest to the largest space between chips.

C. MODEL VALIDATION

For model validation, the numerical results of the present study are compared with the experimental data from three prototypes of the proposed MC LED modules. The \( T_j \) of each package with LED chips and MCPCB mounted on a heat sink were measured under room temperature (\( T_f = 25 °C \)). In our previous work [42], \( T_j \) measurements based on the forward voltage method and IR camera [43], [44] were carried out in the experiments. The value of \( T_f \) was the average of measured data since the forward voltage measurement was conducted on the LED chips in series.

The thermal resistances of calculation and measurement for MC LED module are listed in Table 2 for comparison. \( T_{j,E} \) is the measured mean junction temperature; \( T_{E,c} \) is the edge temperature of MCPCB from the experiment. Great thermal resistance and temperature difference on the plate can induce high thermal stress in the interface of the module [1]. Thus, it is necessary to rearrange the space between chips and optimize the configuration of LED module for obtaining lower \( R_{tot} \). As shown in Fig. 3, the calculations are consistent with the experimental data within the accepted error range of 5% in the same configuration and operating conditions. Therefore, the general analytical solutions are available to apply thermal analysis and optimization on the MC LED module.

<table>
<thead>
<tr>
<th>No.</th>
<th>( T_{j,E} ) (°C)</th>
<th>( T_{E,c} ) (°C)</th>
<th>( R_{tot} ) (°C/W)</th>
<th>( T_{j,E} ) (°C)</th>
<th>( T_{E,c} ) (°C)</th>
<th>( R_{tot} ) (°C/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-1</td>
<td>62.75</td>
<td>29.63</td>
<td>16.90</td>
<td>62.78</td>
<td>28.71</td>
<td>17.38</td>
</tr>
<tr>
<td>7-2</td>
<td>60.13</td>
<td>29.08</td>
<td>15.84</td>
<td>59.05</td>
<td>28.58</td>
<td>15.55</td>
</tr>
<tr>
<td>7-3</td>
<td>57.42</td>
<td>28.25</td>
<td>14.88</td>
<td>57.83</td>
<td>28.71</td>
<td>14.86</td>
</tr>
</tbody>
</table>

Subscripts \( E \) and \( c \) are for experimental and calculated results respectively.
strong correlation with the layout of the heat source and its configuration. Our aim is to optimize both layout and configuration of the module by minimizing the total thermal resistance \( R_{\text{tot}} \). The objective function created by RSM is formulated as

\[
y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ij} x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_i x_j,
\]

where \( a_0, a_i, \) and \( a_{ij} \) are tuning parameters and \( n \) is the number of parameters.

As shown in Fig. 1, the considered design parameters in this study are:
- \( x_1 \): space between the chip,
- \( x_2 \): thickness of the MCPCB, and
- \( x_3 \): thickness of the base plate. The objective function \( y \) denotes \( R_{\text{tot}} \).

The optimum process is implemented by the combination of RSM and GA, which is shown in Fig. 5 and described as follows.

a) The relationships between the design parameters and objective function are generated by utilizing the Box-Behnken DOE method.

b) Forming RSM, and the goodness of fit is judged by coefficient of determination, root mean square error and relative maximum absolute error, etc.

c) The additional design points would be added to construct new RS, if the above prediction error is larger than 5%. If not, the coefficients of the second order RSM for the objective function are determined by nonlinear regression analysis.

d) Using GA to find out the optimal geometries, which are coded by Matlab toolbox code. The best value of objective function for the initial population is obtained by calculation, and the corresponding chromosome is selected as parent. The initial population size is set as 40. The crossover is selected as scattered and the mutation function is chosen to be 0.001. The crossover combines two chromosomes (parents) to produce a new chromosome (offspring).

e) GA solves the optimization problem iteratively based on the biological evolution process in nature. If the minimum fitness values are low, and fewer offsprings are eliminated, optimization will be stopped by meeting an end criterion.

III. OPTIMIZATION METHOD

A. THE CONFIGURATION OF MC LED MODULE

To verify the universality of the optimization method presented in this work, three categories typical layouts of MC LED module are selected to perform the heat transfer characteristics, as shown in Fig. 4. The first category, named of OR, is circular distribution with \( 2^0 + 2^2 + 2^3 + \ldots + 2^n \) \((n = 3)\) chips. \( R_2 - R_1 = R_1 = x_1 \). SQ: \( n^2 \) \((n = 3)\) \( s_2 = x_1 \), and HX: \( 2^0 + 2^1 \times 3 + 2^2 \times 3 + 2^3 \times 3 + \ldots + 2^n \times 3 \) \((n = 3)\).

The objective function created by RSM is formulated by utilizing the Box-Behnken DOE method.

B. OPTIMAL PROCESS

According to Eq. (6) and above discussions, temperature uniformity and thermal resistance of MC LED module show

\[
R_{\text{tot}} = \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ij} x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_i x_j,
\]

where \( a_0, a_i, \) and \( a_{ij} \) are tuning parameters and \( n \) is the number of parameters.

As shown in Fig. 1, the considered design parameters in this study are:
- \( x_1 \): space between the chip,
- \( x_2 \): thickness of the MCPCB, and
- \( x_3 \): thickness of the base plate. The objective function \( y \) denotes \( R_{\text{tot}} \).

The optimum process is implemented by the combination of RSM and GA, which is shown in Fig. 5 and described as follows.

a) The relationships between the design parameters and objective function are generated by utilizing the Box-Behnken DOE method.

b) Forming RSM, and the goodness of fit is judged by coefficient of determination, root mean square error and relative maximum absolute error, etc.

c) The additional design points would be added to construct new RS, if the above prediction error is larger than 5%. If not, the coefficients of the second order RSM for the objective function are determined by nonlinear regression analysis.

d) Using GA to find out the optimal geometries, which are coded by Matlab toolbox code. The best value of objective function for the initial population is obtained by calculation, and the corresponding chromosome is selected as parent. The initial population size is set as 40. The crossover is selected as scattered and the mutation function is chosen to be 0.001. The crossover combines two chromosomes (parents) to produce a new chromosome (offspring).

e) GA solves the optimization problem iteratively based on the biological evolution process in nature. If the minimum fitness values are low, and fewer offsprings are eliminated, optimization will be stopped by meeting an end criterion.

IV. RESULTS AND DISCUSSION

A. OPTIMIZATION ON THE CONFIGURATION OF THE LED MODEL

According to the preliminary tests and geometric constraints of the LED modules, the ranges of the design parameters are selected as 3 mm \( \leq x_1 \leq 10 \) mm; 0.1 mm \( \leq x_2 \leq 2 \) mm; 1 mm \( \leq x_3 \leq 5 \) mm. Numerical simulations of three types for MC LED modules are performed by Matlab through Box-Behnken design. Based on the results in Table 3, the coefficients of the second-order RSM are determined and given in Table 4.

After optimizing objectives with GA, the optimal design parameters of three types of MC LED modules are
TABLE 3. Results of the Box-Behnken design method for three types of modules.

<table>
<thead>
<tr>
<th>Design case</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$y_{\text{OR}}$</th>
<th>$y_{\text{SQ}}$</th>
<th>$y_{\text{HX}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.00</td>
<td>1.05</td>
<td>1.00</td>
<td>7.52</td>
<td>13.35</td>
<td>13.18</td>
</tr>
<tr>
<td>2</td>
<td>3.00</td>
<td>0.10</td>
<td>3.00</td>
<td>1.83</td>
<td>3.16</td>
<td>3.18</td>
</tr>
<tr>
<td>3</td>
<td>10.00</td>
<td>1.05</td>
<td>5.00</td>
<td>6.68</td>
<td>12.13</td>
<td>12.47</td>
</tr>
<tr>
<td>4</td>
<td>10.00</td>
<td>1.05</td>
<td>1.00</td>
<td>6.74</td>
<td>12.27</td>
<td>12.48</td>
</tr>
<tr>
<td>5</td>
<td>6.50</td>
<td>1.05</td>
<td>3.00</td>
<td>6.68</td>
<td>11.73</td>
<td>12.12</td>
</tr>
<tr>
<td>6</td>
<td>3.00</td>
<td>2.00</td>
<td>3.00</td>
<td>8.33</td>
<td>15.00</td>
<td>15.03</td>
</tr>
<tr>
<td>7</td>
<td>6.50</td>
<td>0.10</td>
<td>1.00</td>
<td>1.59</td>
<td>2.96</td>
<td>3.06</td>
</tr>
<tr>
<td>8</td>
<td>6.50</td>
<td>1.05</td>
<td>3.00</td>
<td>6.68</td>
<td>11.73</td>
<td>12.12</td>
</tr>
<tr>
<td>9</td>
<td>10.00</td>
<td>2.00</td>
<td>3.00</td>
<td>7.43</td>
<td>13.63</td>
<td>13.86</td>
</tr>
<tr>
<td>10</td>
<td>3.00</td>
<td>1.05</td>
<td>5.00</td>
<td>7.15</td>
<td>12.73</td>
<td>12.63</td>
</tr>
<tr>
<td>11</td>
<td>6.50</td>
<td>1.05</td>
<td>3.00</td>
<td>6.68</td>
<td>11.73</td>
<td>12.12</td>
</tr>
<tr>
<td>12</td>
<td>6.50</td>
<td>2.00</td>
<td>1.00</td>
<td>7.38</td>
<td>13.35</td>
<td>13.72</td>
</tr>
<tr>
<td>13</td>
<td>6.50</td>
<td>2.00</td>
<td>5.00</td>
<td>7.32</td>
<td>13.08</td>
<td>13.47</td>
</tr>
<tr>
<td>14</td>
<td>6.50</td>
<td>0.10</td>
<td>5.00</td>
<td>1.61</td>
<td>2.75</td>
<td>2.91</td>
</tr>
<tr>
<td>15</td>
<td>10.00</td>
<td>0.10</td>
<td>3.00</td>
<td>1.60</td>
<td>2.75</td>
<td>2.93</td>
</tr>
</tbody>
</table>

TABLE 4. Coefficients of the second-order RSM for three types of modules.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>2.33412</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-0.41947</td>
</tr>
<tr>
<td>$a_2$</td>
<td>8.65627</td>
</tr>
<tr>
<td>$a_3$</td>
<td>-0.10515</td>
</tr>
<tr>
<td>$a_{12}$</td>
<td>-0.05017</td>
</tr>
<tr>
<td>$a_{13}$</td>
<td>0.011227</td>
</tr>
<tr>
<td>$a_{23}$</td>
<td>-0.01077</td>
</tr>
<tr>
<td>$a_{11}$</td>
<td>0.027176</td>
</tr>
<tr>
<td>$a_{12}$</td>
<td>-2.45802</td>
</tr>
<tr>
<td>$a_{13}$</td>
<td>2.27E-03</td>
</tr>
</tbody>
</table>

determined as follows: OR: $x_1 = 6.533$ mm, $x_2 = 0.10$ mm, $x_3 = 3.45$ mm, $y = 1.59$ °C/W, $R_t = 1.99$°C/W; SQ: $x_1 = 6.627$ mm, $x_2 = 0.10$ mm, $x_3 = 3.865$ mm, $y = 2.82$ °C/W,$R_t = 2.33$°C/W; HX: $x_1 = 6.365$ mm, $x_2 = 0.10$ mm, $x_3 = 4.765$ mm, $y = 2.84$ °C/W, $R_t = 2.34$°C/W. Therefore, the heat dissipation performances of the modules are estimated based on the determined optimal design parameters.

B. SENSITIVITY ANALYSIS

1) EFFECTS OF DESIGN PARAMETERS
By varying the value of the selected parameter, the effects of each design parameter on the thermal resistance can be discussed. The heat input and the ambient temperature are fixed at 0.28 W per chip and 25°C, respectively. Fig. 6 shows the effects of design variables on the total thermal resistance.

As shown in Fig. 6(a), the $R_{tot}$ of OR and SQ decrease slightly (by ∼7%) with increasing $x_1$. Thus, the optimum $x_1$ for OR and SQ are determined as 6.533 mm and 6.627 mm, respectively. The $R_{tot}$ of HX decrease until $x_1$ increase to 6.365 mm, and then increase with increasing $x_1$. Therefore, increasing the space between the chips is beneficial to improve heat transfer. Fig. 6(b) shows the effects of the MCPCB thickness $x_2$ on $R_{tot}$. Obviously, $R_{tot}$ increases rapidly when $x_2$ is from 0.1 mm to 1 mm and especially in the range of 0.3 mm to 0.5 mm. Therefore, the thickness of MCPCB has negative effects on the improvement of heat transfer. Designer should choose a thinner MCPCB or remove MCPCB from the module. Thus the LED chips is better to be bonded on a base plate with integrated circuit directly.

As shown in Fig. 6(c), the effect of $x_3$ on $R_{tot}$ is relatively small (<7%) compared with that of $x_2$.

2) SENSITIVITY OF THE GEOMETRIC PARAMETERS
A sensitivity analysis is carried out to determine the optimum mode of the effective parameters on the performance of the module. The sensitivity of the geometric parameters are the derivative of the output variable ($y$, the minimum thermal resistance) to input parameters ($x_1$, $x_2$, $x_3$), which are
calculated as follows:

$$\frac{\partial y}{\partial x_1} = a_1 + a_{12}x_2 + a_{13}x_3 + 2a_{11}x_1$$ (10)

$$\frac{\partial y}{\partial x_2} = a_2 + a_{12}x_1 + a_{23}x_3 + 2a_{22}x_2$$ (11)

$$\frac{\partial y}{\partial x_3} = a_3 + a_{13}x_1 + a_{23}x_2 + 2a_{33}x_3$$ (12)

The positive value of the sensitivity indicates an increase in the objective function with the increasing input parameters, and the negative value represents a reduction. According to the sensitivity results presented in Fig. 7 and Fig. 8, it can be concluded that:

1) The sensitivity of the space between the chips (x1) for OR and SQ are negative, indicating R_{tot} reduce as x1 are increased; For HX, the sensitivity of x1 is positive, which means that R_{tot} increases with increasing x1. It is explained why the R_{tot} of HX in Fig. 6(a) first decreases to the trough at x1 = 6.365 mm and then increases as x1 is increased.

2) The thickness of MCPCB (x2) has a stronger impact on R_{tot} than x1 and x3. The sensitivity of x2 is positive, which means that the minimum thermal resistance reduces with it. This is fully consistent with the results of Fig. 6(b).

3) The sensitivity of thickness of the base plate (x3) is negative, indicating that increasing x3 can reduce the R_{tot}. However, it is far less than that of x1 and x2.

4) Overall, the effects of configuration parameters on the thermal performance of MC LED module are studied from qualitatively to quantitatively. All results are of great significance in the selection of geometric parameters of the module to improve its thermal performance.

5) This optimization work is of high efficiency. And it is more available for two-dimensional or equivalent two-dimensional case.

C. THERMAL AND OPTICAL PERFORMANCE OF THE ENHANCED MC LED MODULE

The heat dissipation performance and luminous efficacy of the optimized MC LED modules are compared with that of the original modules (x1 = 3 mm, x2 = 1 mm, x3 = 5 mm). Fig. 9 and Fig. 10 show the temperature
distribution and thermal resistance of three types of LED modules before and after optimization, respectively. It is obvious that three types of modules obtain lower $T_j$ and $R_{\text{tot}}$ after optimization. $T_j$ of each module is decreased by $\sim 62\%$. $R_{\text{tot}}$ of OR, SQ and HX module drop 92.8%, 96.2% and 96.3%, respectively. More uniform temperature distribution leads to lower thermal stress and higher reliability for the module.

The luminous efficacy of the LED module, which was defined as “luminous flux/power consumption” [45], is dependent on the junction temperature of the LED die.

$$E = E_0[1 + k_e(T_j - T_0)],$$

(13)

where $E_0$ (95.63 lm/W) denotes the rated efficacy at the rated temperature ($T_0 = 64.90 \degree C$), and $k_e$ is the relative reduction rate of efficacy with increasing temperature. $k_e$ is calculated from the measured luminous efficacy of MC LED module in Section II under different $T_j$, and is about -0.0015. Fig. 11 shows the luminous efficacy of three types of MC LED modules before and after optimization according to Eq. (13). Also, the $T_j$ and $E$ of the module with 5 times of rated heat input is calculated based on the general analytical solution and optimized model. The result shows that the luminous efficacy decreases slightly under 5 times of rated heat input. It is obvious that the optimized module can allow stable operation under high power input conditions, and emit a large amount of light energy.

V. CONCLUSIONS

In this study, based on the response surface methodology and genetic algorithm, the configuration of MC LED module is optimized. The thermal resistance and temperature distribution of MC LED module with multiple heat sources are calculated by using general analytical solution. The main conclusions are listed as below:

1) The effects of configuration design parameters, including space between chips ($x_1$) and the thickness of MCPCB ($x_2$) and base plate ($x_3$), on thermal resistance ($y$) are analyzed from qualitatively to quantitatively.

2) After optimizing objectives with GA, the optimal design parameters of three types of modules are determined, verifying the universality of the optimization method presented in this work.

3) The sensitivity analysis is performed based on the optimum data. The results show that $x_2$ has a stronger impact on $R_{\text{tot}}$ than $x_1$ and $x_3$. The sensitivity of $x_2$ is positive, while that of $x_1$ and $x_3$ are negative. It indicates that $R_{\text{tot}}$ increases with the increased thickness of MCPCB, and reduces as the space between chips...
increasing. The effect of the thickness of base plate is slight. Thus, designer should choose a thinner MCPCB, or solder chips on a base plate with integrated circuit directly. Moreover, increasing the space between the chips is beneficial to improve heat transfer.

4) Obviously, three types of MC LED modules have lower $T_j$ and $R_{th}$ after optimization. Encouragingly, the luminous efficacy decreased slightly with increasing $T_j$ and input power, indicating that the optimized module can emit a large amount of light energy under high power input conditions.

The optimization results are of great significance in the selection of geometric parameters to improve the performance of MC LED module with different types of layout.

REFERENCES

HONG-YU TANG (S’16) received the B.S. and M.S. degrees in microelectronic packaging technology from Guilin University of Electronic Technology, Guilin, China, in 2010 and 2013, respectively. She is currently pursuing the Ph.D. degree with the Faculty of Electrical Engineering Mathematics and Computer Science, Delft University of Technology, Delft, The Netherlands. Her current research interests include the thermal management of high-power devices, and advanced material (micro-/nano-material) applications.

HUAI-YU YE (M’16) received the B.S. degree from Shanghai Jiao Tong University, China, and the M.A. and Ph.D. degrees from Delft University of Technology, The Netherlands. He was with the Materials Innovation Institute and Netherlands Organization for Applied Scientific Research as the Materials Innovation Institute and Netherlands Organization for Applied Scientific Research as a Senior Researcher. He is currently a Full-time Professor with Key Laboratory of Optoelectronic Technology and Systems, Education Ministry of China, and the College of Optoelectronic Engineering, Chongqing University, China. His research interests include temperature sensors, computational fluid dynamics in MEMS, thermal management in high-power density electronic devices, microscale/nanoscale nonequilibrium thermodynamics, and microscale/nanoscale energy transport and conversion. He received the One-Hundred Talent Program Scholars of Chongqing University in 2016.

XUAN-PING CHEN (M’15) received the B.Eng. degree from Chongqing University (CQU), China, the M.Sc. degree from Dresden University of Technology, Germany, and the Ph.D. degree from Delft University of Technology, The Netherlands. He was Postdoctoral Researcher with Tsinghua University, China, for two-years. He is currently a full-time Professor with the College of Optoelectronic Engineering, CQU. He is also the Distinguished Expert of Chongqing Municipality, China, and the Technical Committee Member of China Advanced Semiconductor Industry Innovation Alliance. He published about 80 technical papers (over 50 SCI journal publications) and four books. He holds 41 patents. His research interests include electronic materials, electronic packaging, chemical and biological sensors, LED, and nanodevices. He received the One-Hundred Talent Program Scholars of Guangxi in 2013 and the One-Hundred Talent Program Scholars of Chongqing Municipality in 2016, respectively.

CHENG QIAN (M’16) received the B.S. and M.S. degrees in materials science and technology from Beijing Institute of Technology in 2003 and 2006, and the Ph.D. degree in aerospace engineering from Delft University of Technology in 2013. After that, he joined the Changzhou Institute of Technology Research for Solid State Lighting, China. Since 2014, he started his postdoctoral fellowship with the State Key Laboratory of Solid State Lighting, Institute of Semiconductors, Chinese Academy of Science. His current work covers multiple subjects, including LED package/luminaire failure analysis and simulations, development of accelerating test techniques for LED luminaires, lifetime predictions on photonic, and chromatic parameters of the LED package/luminaire. His research interests include the designing reliability of LED luminaires and systems using the combined knowledge of multiphysics numerical simulations and statistical theories.
GUO-QI ZHANG (M’03–F’14) received the Ph.D. degree in aerospace engineering from Delft University of Technology, Delft, The Netherlands, in 1993.

Since 2013, he has been a Chair Professor with the Department of Microelectronics, Delft University of Technology. He had been with Philips for 20 years as the Principal Scientist from 1994 to 1996, the Technology Domain Manager from 1996 to 2005, the Senior Director of Technology Strategy from 2005 to 2009, and a Philips Fellow from 2009 to 2013. He also had part-time appointments as a Professor with the Technical University of Eindhoven, The Netherlands, from 2002 to 2005, and as a Chair Professor with Delft University of Technology from 2005 to 2013. He is one of the pioneers in developing the More than Moore (MtM) strategy when he served as a Chair of the MtM Technology Team of European’s Nanoelectronics Platform in 2005. He has authored more than 400 papers, including over 150 journal papers, and three books, and 17 book chapters. He holds more than 100 patents. His research interests include heterogeneous micro/nanoelectronics packaging, system integration, and reliability. He received the Outstanding Contributions to Reliability Research Award from the European Center for Micro/Nanoreliability, in 2007, the Excellent Leadership Award at EuroSimE, the Special Achievement Award at ICEPT, and the IEEE Components, Packaging, and Manufacturing Technology Society Outstanding Sustained Technical Contribution Award in 2015.

* * *