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# Phosphor distribution optimization to decrease the junction temperature in white pc-LEDs by genetic algorithm

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ABSTRACT

In this study, genetic algorithm (GA) was utilized to optimize the phosphor distribution to decrease the junction temperature of white phosphor-converted light-emitting diodes (pc-LEDs). The key steps of the GA were introduced, including selection, crossover, and mutation. Both the junction temperature and the entransy dissipation of each evolution were calculated. It was found that with evolutions, the phosphor particles tend to build a "thermal bridge" between the chip and the convective boundary and spread along the convective boundary. The junction temperature decreases from ~157.5 °C to ~150 °C and the entransy dissipation decreases from ~18 W K to ~6 W K. The least entransy dissipation principle was demonstrated to be the rule that governs the optimization processes.



## 1. Introduction

In recent decades, light-emitting diode (LED) technology has created more turmoil in the lighting industry than anything occurring over the previous century. The conventional incandescent and fluorescent light sources are increasingly being replaced by more energy-efficient, longer-lived, and environmentally friendlier white LEDs [1–5]. However, white LEDs still suffer from challenges related to brightness, efficiency, reliability, and performance. Due to the limited optoelectronic conversion efficiency of LED chip, more than 70% of the input power converts into heat. Heat, however, plays a negative role that heat will increase the junction temperature, which is the most important thermal parameter in LEDs. High junction temperature will decrease the internal quantum efficiency, reduce the luminous output, degrade the packaging materials, lower the reliability, and shorten the lifetime, etc. [1,2]. Thermal management, hence, is important for high power white LEDs and its primary goal is to decrease the junction temperature.

According to the current state-of-the-art white LEDs, the phosphor-converted LEDs (pc-LEDs) are the most frequently-used method to generate white light [1,2,6]. In pc-LEDs, since the phosphor silicone matrix is coated on the chip, it badly influences the chip heat dissipation. Moreover, in the pc-LEDs, besides the heat generated in the active layer of the chip, it has been reported that phosphors also generate heat [7–11]. Based on the Kubelka–Munk theory, we also proposed a method to calculate the heat generation in phosphors [12,13]. Although the heat generated in phosphors is much less than that in chip, there is no good heat dissipation medium for the phosphor particles since they are embedded in silicone with low thermal conductivity (~0.2 W/(m K)). The phosphor self-heating, not only affects the phosphor characteristics, but also increases the LED junction temperature.

So far, most thermal management methods for LED packages focus on enhancing the heat dissipation outside of the package, like air cooling, liquid cooling, etc. [14–17]. According to the Bar-Cohen star-shaped thermal resistance model, part of heat will be dissipated through phosphor layer, lens, to the ambient air [18,19]. However, few reports focus on the internal thermal management that aims at improving the heat dissipation inside the LED package, more specifically dealing with the phosphors. It is affirmative that the internal thermal management will benefit the external heat dissipation.

In this study, we focused on the internal thermal management of pc-LED package. The phosphor distribution in pc-LEDs was optimized to decrease the junction temperature by genetic algorithm (GA). The details about the GA procedure dealing with this problem were introduced. The evolutions about the phosphor distributions were presented and the corresponding junction temperature and

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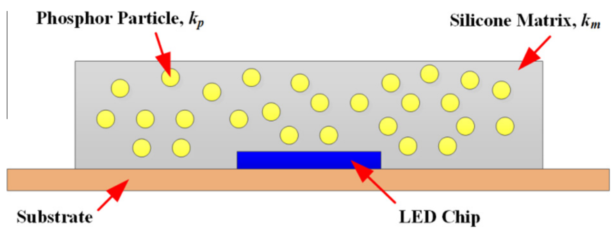


**Fig. 1.** Schematic of pc-LED package.

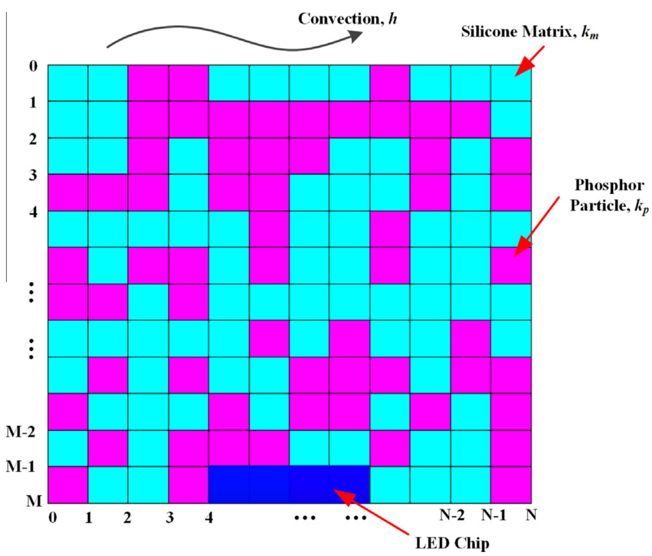


**Fig. 2.** Calculation model for phosphor distribution optimization.

entransy values were evaluated. At last, the optimized phosphor distribution was given.

## 2. Problem statement

In pc-LEDs, the mixture of phosphor particles and silicone matrix is dispersed onto the LED chip that is mounted onto the substrate previously. The schematic of the pc-LEDs is pictured in Fig. 1. The thermal conductivities of the phosphor particle and the silicone matrix are $k_p$ and $k_m$, respectively. In the phosphor layer, it is reported that the phosphor distribution, due to relatively high thermal conductivity of phosphors (~13 W/(m K)), influences the heat conduction processes in silicone [8–10]. But what's the best phosphor distribution that makes the LED junction temperature lowest? This is the exact motivation behind this study and the following part clarifies the detailed solving procedure.

To optimize the phosphor distribution to obtain the lowest junction temperature, we established a model, as shown in Fig. 2. The width and height of the phosphor layer is $L$ and $H$, respectively. The chip dimension is one third of the width and it is placed in the middle of the $x$ axis. The phosphor layer is divided into $M \times N$ grids along the $y$ and $x$ axes respectively, and each grid corresponds to a unit cell, i.e. either one phosphor particle or silicone matrix. The magenta grids in Fig. 2 denote the phosphor particle with thermal conductivity $k_p$. The cyan grids in Fig. 2 denote the silicone matrix with thermal conductivity $k_m$. As the original intention of this study, we put aside the external thermal management and mainly focus on the internal thermal management of the pc-LED packages. So, in the model, we neglected the substrate and only the top surface is cooled with a convective heat-transfer coefficient, $h$, and

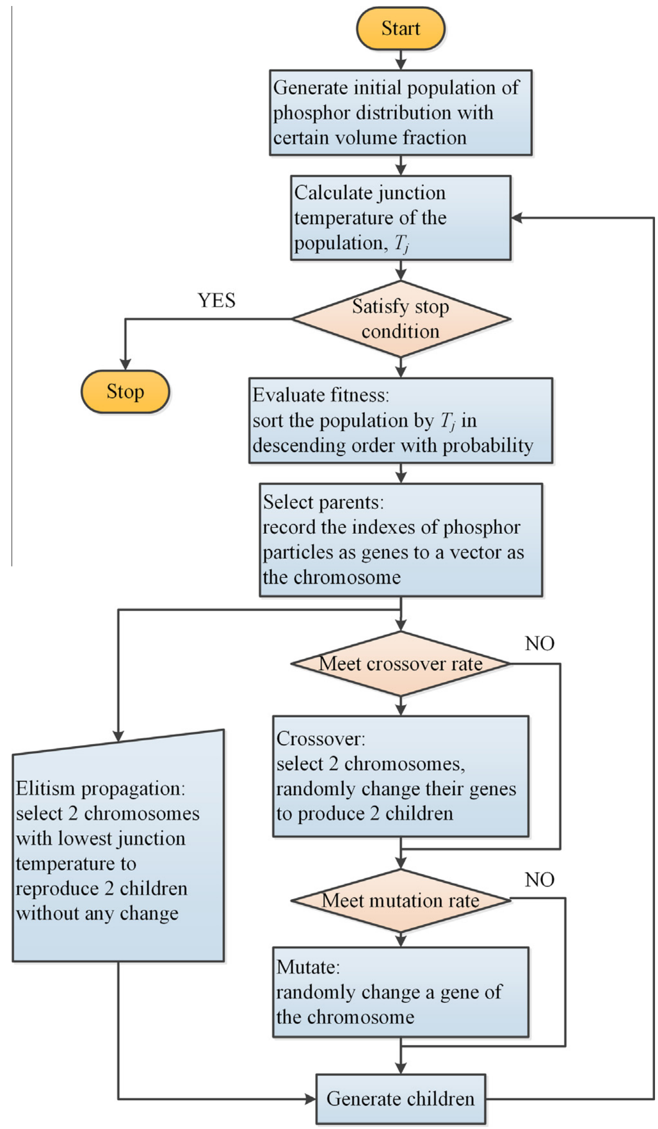


**Fig. 3.** Flowchart of GA procedure.

other surfaces are insulated. The heat sources in this model contain two parts: LED chip and phosphor particles. The LED chip is assumed as a homogenous heat source with power of $q_c$. Each phosphor particle is also assumed as a homogenous heat source with the power of $q_p$. It is predicted that the total phosphor heat generation may be not homogenous because it is dependent on the distribution of phosphor particles. The phosphor volume fraction, $\phi$, is defined as $N_p/(M \times N)$, where $N_p$ is the number of phosphor particles. The mathematical description of this problem is

$$\begin{cases} \min(\max T) \\ s.t. \nabla(k_i \nabla T_i) + q_i = 0, \; i = p, m \end{cases} \tag{1}$$

with boundary conditions

$$\begin{cases} \partial T/\partial y = q_c/k_i, & \text{at } y = 0; 1/3L \le x \le 2/3L \\ \partial T/\partial y = 0, & \text{at } y = 0; x < 1/3L, x > 2/3L \\ \partial T/\partial y = h/k_i(T - T_a), & \text{at } y = H \\ \partial T/\partial x = 0, & \text{at } x = 0, L \end{cases} \tag{2}$$

where $q_m$ equals zero because silicone will not generate heat. Another constraint condition is the phosphor volume fraction $\phi$. The precise solution to such a nonlinear problem is not easy and

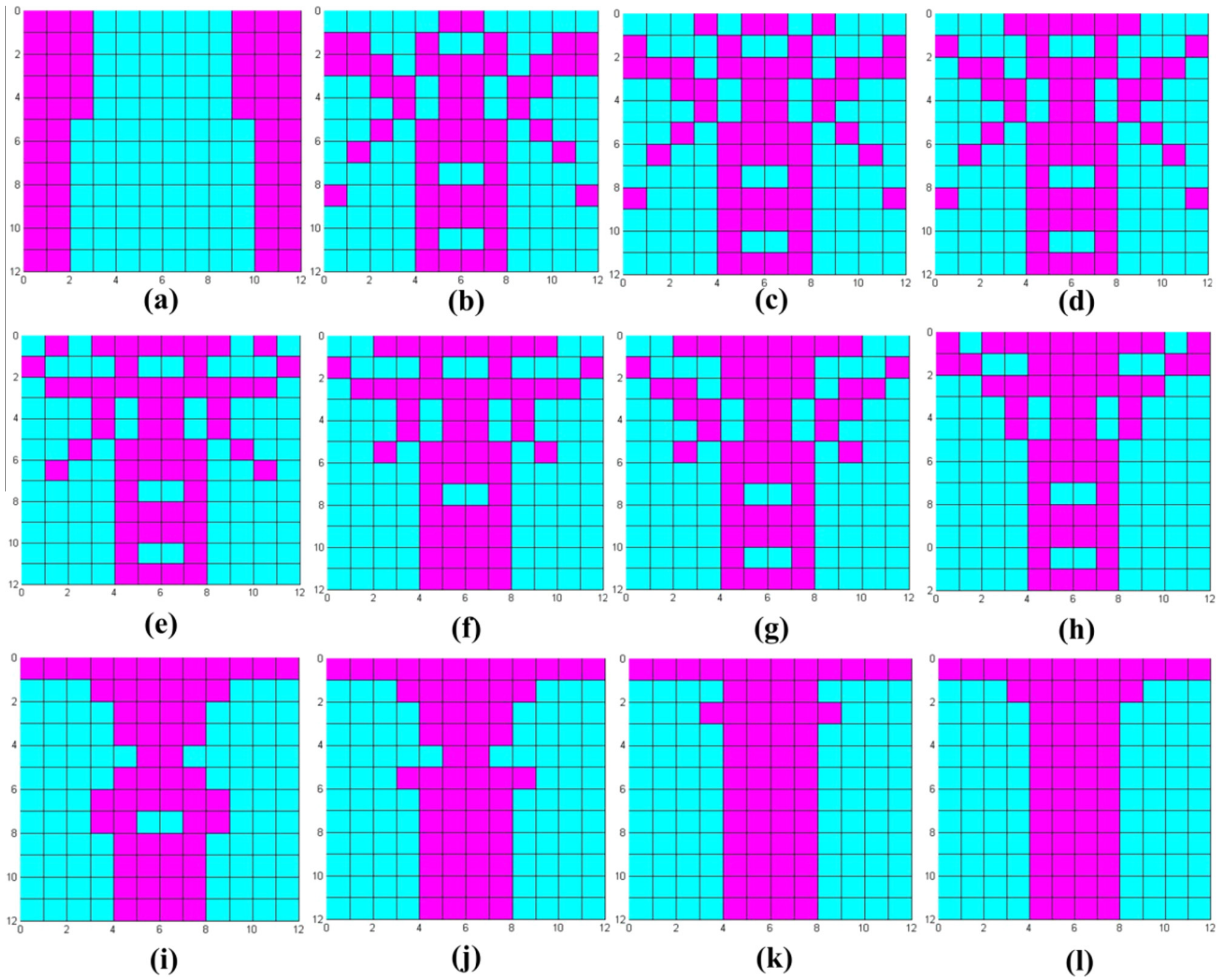


**Fig. 4.** Selected 12 evolution generations for 12 × 12 grids with volume fraction of 0.4.

numerical method is preferred. For certain phosphor distribution, the temperature field can be calculated by finite difference method (FDM). For every phosphor distribution, the new temperature filed calculation is required though it is kind of time-consuming.

The remaining problem is that how to find out the right phosphor distribution that corresponds to the lowest junction temperature. If we traverse all the distributions, we can find out the best distribution but must be exhausted. Here, to avoid such embarrassing situation, we adopted the genetic algorithm (GA) to find out the best distribution without traversing all the distributions.

## 3. Genetic algorithm

GA is a global search algorithm that is based on the Darwinian theory of natural selection and survival of fittest one that exists in the genetics of the species [20,21]. The GA generally consists of population initialization, selection, crossover, and mutation processes. The flowchart of GA procedure in this study is shown in Fig. 3. The key steps in Fig. 3 are introduced in detail as follows.

### 3.1. Initialization

At the beginning, the population size, the crossover rate, the mutation rate, and the number of generations are set. For certain

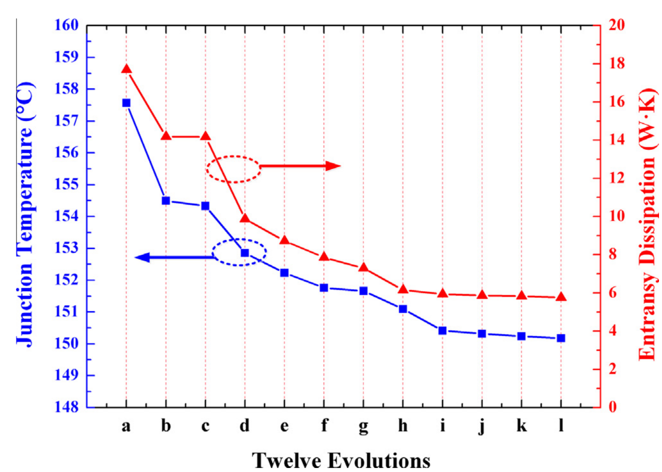


**Fig. 5.** Junction temperature and entransy dissipation of the selected 12 evolution generations.

volume fraction, a certain number (population size) of phosphor distributions are generated randomly as the initial population. We reshape each distribution into a vector as the individual in the population. For each individual, the temperature field is calculated and the junction temperature, $T_j$, is obtained.

### 3.2. Evaluate fitness

We sort the populations by their junction temperature in descending order. The fitness value of $i_{th}$ individual is defined as $2i/(P(P+1))$, where $P$ is the population size [21]. The fitness function can also be other formula but should have such a characteristic that the lower the junction temperature is, the larger the fitness of the corresponding individual is. The values of the fitness imply the probability of the individual to be chosen for propagation.

### 3.3. Selection

Depending on the fitness function, parent generations are selected to participate in the propagation for a new generation. For saving computation time, we encoded the indexes of the phosphor particles as vectors, which are the chromosomes rather than the individual. This is a really effective tip to speed up to obtain the final global optimum result. To keep good genes, the elitism strategy is applied that the best 2 chromosomes in every generation propagate to the next generation without any change. The chromosomes hold genes that participate in the following crossover or mutation processes. But at the end of each generation of propagation, we decoded the chromosomes and returned to the individuals based on the chromosomes for the calculation of temperature fields for the next generation.

### 3.4. Crossover

We randomly generate a number between 0 and 1. If the random number is smaller than the crossover rate, the chromosomes of the two parents are randomly exchanged to breed the child generation. Otherwise, no crossover happens and the child generations are the exact copy of the parent generations. Since the chromosomes are the indexes of the phosphor particles, no matter in the parent generation or in the child generation, it is not allowed that there exist same numbers in the chromosomes. This rule is essential especially in the child generation. If it happens, we should change the crossover position in the chromosomes or forbidden the crossover at this generation.

### 3.5. Mutation

In order to maintain the diversity of the individuals, the chromosomes are allowed for a small chance of mutation. Mutation changes one or more genes in a chromosome randomly. Similar to crossover, the mutation does not allow same number in the chromosomes. This can add entirely new genes to the gene pool. With the mutation, GA may be able to achieve global optimum solution rather than being trapped in local optimum solution.

### 3.6. Termination

The optimization process is repeated until a termination condition has been reached. The termination condition can be two kinds:

(a) The number of evolution generations has been reached.
(b) The lowest junction temperature in each generation does not change over 800 generations.

## 4. Results and discussions

Based on above algorithm, we optimized the phosphor distribution to obtain the lowest junction temperature of pc-LEDs. For calculation convenience, the grid scale is selected as 12 × 12. The thermal conductivity of phosphor particle and silicone matrix are 13 and 0.1 W/(m K). The volume fraction of phosphors is 0.4. The population size is 20 and the crossover rate and mutation rate are 0.9 and 0.2, respectively. The total heat power in chip and phosphors is 1 W and 0.2 W, respectively. The convective heat-transfer coefficient is 10 W/(m$^2$ K) and the ambient air is at 20 °C. The number of evolution generations is 2000, which should be large enough to ensure the global optimum result.

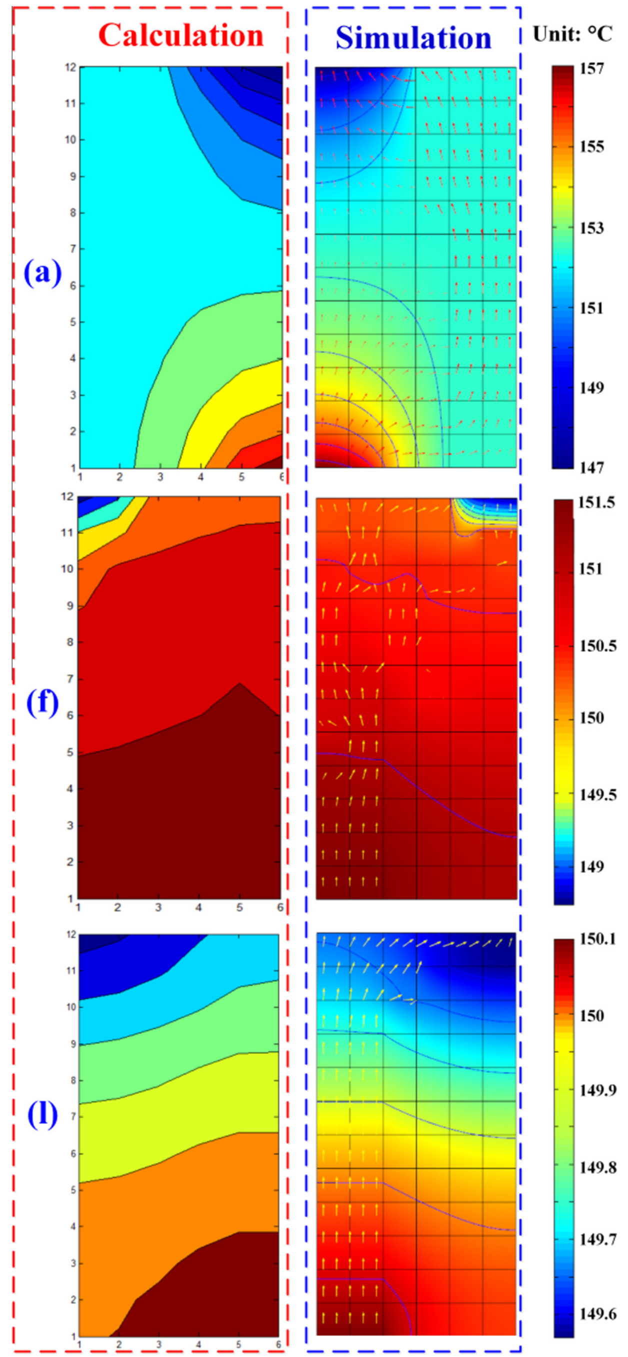


**Fig. 6.** Comparisons of temperature fields of evolution generation obtained by FDM and COMSOL.

The selected 12 evolution generations are plotted in Fig. 4 and the corresponding junction temperature of each evolution generation is shown in Fig. 5. Fig. 4(a) is the initial distribution whose junction temperature is the largest. It is seen in Fig. 4 that with evolutions, the phosphor particles (with high thermal conductivity) tend to form a "thermal bridge" between the chip and the convective boundary, and the remaining particles tend to spread along

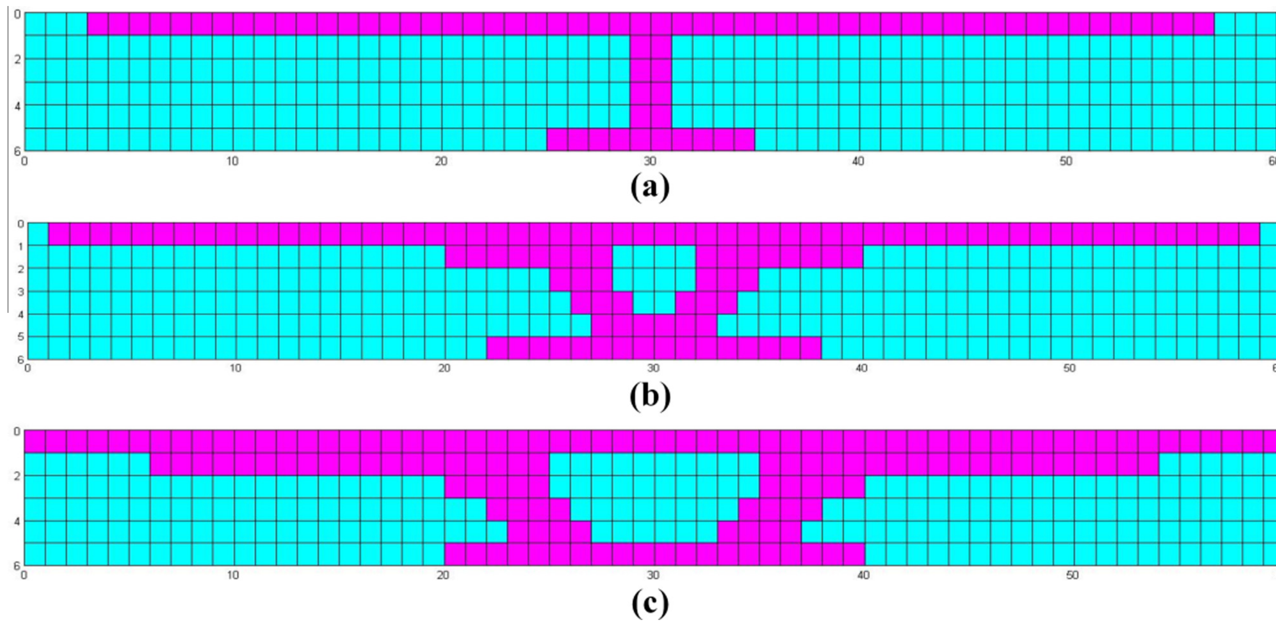

**Fig. 7.** Optimized phosphor distribution for 60 × 6 grids with different volume fractions: (a) 0.2, (b) 0.3 and (c) 0.4.

the convective boundary. The heat in chip can be conducted to the boundary for cooling along the "thermal bridge" relatively easily. And the particles spreading along the convective boundary imply the enhancement of convective heat transfer. Both the "thermal bridge" and the spreading along convective boundary benefit the heat dissipation. It is seen in Fig. 5 that with evolutions, the junction temperature decreases gradually from ~157.5 °C to ~150 °C. Obviously, the junction temperature is larger than usual, which is because we neglect the heat dissipation through the substrate to the ambient air.

To explore the reasons behind the evolution phenomena, the concept of entransy dissipation was invoked, which can be used to define the efficiency for heat transfer process [22–24]. Guo et al. proposed the least entransy dissipation principle that leads to the minimum difference between the two boundary temperatures for the heat flux boundary in this study [22]. He also pointed out that the least entransy dissipation principle corresponds to the minimum equivalent thermal resistance of a system [22]. The entransy dissipation in the study can be calculated as

$$\Phi_G = \underbrace{-\int_S \mathbf{n}\cdot(\mathbf{q}T)dS}_{G_f} + \underbrace{\int_V \dot{q}_s T dV}_{\dot{G}} = \underbrace{\sum\nolimits_{in} A_c q_c T_c - \sum\nolimits_{out} AqT}_{G_f} + \underbrace{\sum\nolimits_{N_p} q_p T V_g}_{\dot{G}} \quad (3)$$

where $G_f$ is the net entransy dissipation on all the boundaries, and $\dot{G}$ is the entransy dissipation due to the inner heat sources of phosphors. $G_f$ can be calculated by the entransy difference between the chip boundary and the convective boundary. $V_g$ is the grid volume.

The entransy dissipations for the selected 12 evolution generations were calculated according to Eq. (3) and plotted in Fig. 5. It is seen that with evolutions, the entransy dissipation decreases from ~18 W K to ~6 W K. The trend of entransy dissipation agrees well with that of the junction temperature curve. The decrease of entransy dissipation means the drop of equivalent thermal resistance. With evolutions, the thermal resistance decreases gradually, and the heat can be more easily dissipated, resulting in the decrease of junction temperature. The optimization process of the phosphor distribution is the process to minimize the entransy dissipation or the equivalent thermal resistance. Therefore, the fundamental reason behind the evolutions is the least entransy dissipation principle.

To more vividly observe the variations of the temperature fields along the evolutions, three evolutions were selected from Fig. 4 as the examples and the FDM calculation results were shown in Fig. 6. Besides the FDM calculations, the commercial software package COMSOL Multiphysics 4.3 was also employed to simulate the temperature fields for comparisons. From Fig. 6, it is seen that both temperature fields calculated by FDM or COMSOL are similar, and the maximum temperature locates at the LED chip. It is also seen that heat tends to be conducted along the "thermal bridge" composed by the phosphor particles. Therefore, the phosphor distribution, corresponding to the morphology of the "thermal bridge", influences the temperature field greatly. With evolutions, the maximum temperature decreases and temperature gradient decreases as well. It is proven that the temperature field is optimized along the evolutions of phosphor distributions.

To simulate the pc-LED package with higher precision, we built another model that contains 60 × 6 grids. The width and height are both according to the dimensions of a real leadframe package that $L$ is 3 mm and $H$ is 300 μm. The dimensions of each grid are $50 \times 50\ \mu m^2$. For such case, the population size and the number of evolution generations must be enhanced to guarantee the final global optimum result. Other conditions are kept the same as above model. The optimization results of phosphor distributions with different phosphor volume fractions are shown in Fig. 7. It is seen that the phosphors build a similar "thermal bridge" between the chip and convective boundary and spread along the convective boundary. When the volume fraction was low (like 0.2), there is only one "thermal bridge"; while two "thermal bridge" may appear when the volume fraction increases to 0.3, 0.4 or even higher. The chip and convective boundaries may not be filled with phosphor particles entirely, which implies that the phosphor particles tend to primarily build a "thermal bridge" rather than primarily spread along the chip or convective boundaries. No matter what the number of "thermal bridge" is or whether the chip and convective boundaries are filled entirely, it is calculated that the junction temperature is decreasing along the evolutions of phosphor distributions. It is perceived that least entransy dissipation principle is also the rule that governs the optimization processes.

Since the LED is a kind of optoelectronic device, both the optical performance and thermal behaviors are important. In this study, we mainly discussed on the effect of phosphor distribution on the thermal behaviors. But from the optimized results, we can see that the phosphor particles spread along the top convective surface homogeneously, which is also beneficial to the optical performance. Uniform distribution of phosphor particles on the top surface results in homogeneous color conversion, which would enhance the uniformity of color temperature (CT) or correlated color temperature (CCT).

## 5. Conclusions

In this study, genetic algorithm (GA) was used to optimize the phosphor distribution to decrease the junction temperature of phosphor-converted light-emitting diodes (pc-LEDs). The key steps of the GA were introduced and the temperature fields were calculated by finite difference method (FDM). It was found that with evolutions, the phosphor particles tend to build a "thermal bridge" between the chip and the convective boundary and spread along the boundary. When the phosphor volume fraction increases, two "thermal bridges" might appear. To further explore the fundamental reason behind the evolutions, the junction temperature and entransy dissipation of each generation were calculated. It was found that with evolutions, the junction temperature decreases from $\sim$157.5 °C to $\sim$150 °C and the entransy dissipation decreases from $\sim$18 W K to $\sim$6 W K. The decrease of entransy dissipation implies that the heat can be dissipated to the ambient air more easily along the evolutions. The least entransy dissipation principle was demonstrated to be the rule that governs the optimization processes.

## Conflict of interest

None declared.

## Acknowledgments

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