Results in Physics 12 (2019) 361–367

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Lifetime prediction of a multi-chip high-power LED light source based on artificial neural networks

Hongwei Liu[a], Dandan Yu[a], Pingjuan Niu[b], Zanyun Zhang[a], Kai Guo[a], Di Wang[b], Jianxin Zhang[b], Xin Ma[c], Chengkui Jia[a], Chaoyu Wu[d]

[a] School of Electronics and Information Engineering, Tianjin Polytechnic University and also with the Tianjin Key Laboratory of Optoelectronic Detection Technology and System, Tianjin 300387, China
[b] School of Electronics and Information Engineering, Tianjin Polytechnic University and also with the Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology, Tianjin 300387, China
[c] School of Computer Science & Software Engineering, Tianjin Polytechnic University, Tianjin 300387, China
[d] Tianjin Sanan Optoelectronic Co., Ltd, Tianjin, China

ARTICLE INFO

Keywords:
Artificial neural network (ANN)
Light-emitting diodes (LED)
Lifetime prediction
Photo-electro-thermal (PET) multiphysics coupling

ABSTRACT

A high power light-emitting diodes (LED) light source, which is assembled by many LED chips and heat sink, has a not uniform temperature distribution at working condition. Analysis and prediction of a high-power LED system lifetime are complicated and time-consuming.

In this study, two artificial neural networks (ANN) are employed to simplify the LED lighting system's lifetime prediction and increase the precision of such analysis. The temperature distribution of the high power light source is calculated by Finite element method (FEM) with LED chip photo-electro-thermal (PET) ANN. With the precise LED temperature distribution, the lifetime for multi-chip high-power LED light source can be predicted by lifetime ANN.

The PET ANN is used to simplify the multi-physics coupling in LED PET analyzing. The lifetime ANN can predict the lifetime of a LED chip across a wide range of temperatures and not merely corresponding to several testing and interpolation points.

This work aims to rapidly analyze multi-chip high-power lighting systems characteristics. The repeated tests and calculations of PET and lifetime are avoided with this method. This approach presents a new and effective way to assess the reliability of high-power LED light source.

Introduction

As an electro-luminance device, the lifetime of LED is affected by input current, device temperature, and luminance efficiency. The commercial LED light output maintenance measurement and prediction are based on LM-80-08 and TM-21-11 extrapolations [1,2].

Many methods are used to accelerate the testing time and improve the accuracy of the measurement. X. Wang and K. Qian [3] proposed a method for estimating the lifetime of the InGaN/GaN LED chip by analysing the density of nonradiative recombination defects. Huang et al. [4] proposed a multiple-stress-based predictive model (MSBPM) to assess the lifetime of LED and a self-designed adaptive genetic algorithm was developed to identify the unknown parameters of the MSBPM. Ruknudeen et al. [5] presented a model-based prognostic approach that uses particle filtering (PF) to predict the remaining useful life for high power white LEDs. There are other ways to assess the lifetime of LED [6–9]. All the above-mentioned works focus on single LED chip characteristic. But multi-chip light source (Fig. 1) with same type LEDs or different type LEDs is a most commonly used application. Padmasali et al. [10] presented some different prognostic algorithms to estimate the L70 life time of LED luminaires. Zhang et al. [11] proposed an optimized model by a Weibull luminance degradation function and an exponential function to estimate the lifetime of LED-based light bars. Both need to be derived directly and calculated repeat. Qian et al. [12] developed a luminous flux depreciation method to reduce the test time. But the test time within 2000 h is still very long and needs to be carried out at high temperatures about 55 °C test temperature. Davis et al. [13] used the accelerated stress tests at more aggressive temperature and

E-mail addresses: liuhongwei@tjpu.edu.cn (H. Liu), 1630091273@stu.tjpu.edu.cn (D. Yu), niupingjuan@tjpu.edu.cn (P. Niu), zhangzanyun@tjpu.edu.cn (Z. Zhang), 1530091090@stu.tjpu.edu.cn (K. Guo), 1731045233@stu.tjpu.edu.cn (D. Wang), zhangjianxin@tjpu.edu.cn (J. Zhang), maxin@tjpu.edu.cn (X. Ma), ckjia@tjpu.edu.cn (C. Jia), wcy@sanan-e.com (C. Wu).

https://doi.org/10.1016/j.rinp.2018.11.001
Received 9 October 2018; Received in revised form 1 November 2018; Accepted 1 November 2018
Available online 10 November 2018

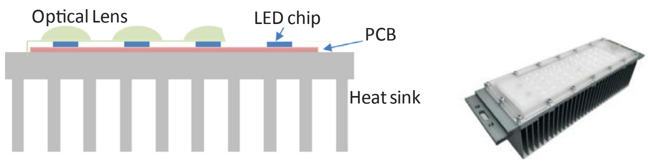

Fig. 1. A multi-chip high power LED light source.

humidity for the reliability performance of Two-channel tunable white lighting systems. But there still be thousands of hours.

When the relevant lifetime measurements concerning a single LED chip have been completed, an additional measurement must be performed for the multi-chip LED light source using the LM-80 test. Although the light source or light module comprises the same type of LED chips, this measurement is essential because the temperature of each LED chip is different in a multi-chip high-power LED module at working condition. Specifically, for a high-power lighting system, this variation can be as high as 30 °C [14–16].

Therefore, estimating LED reliability in a multi-chip high-power system with a single temperature LM-80-08 test statistic is inaccurate. For a high-power light source, additional 6000 h light output maintenance measurement is required, which is unacceptable for some manufacturers and researchers.

For the multi-chip high-power LED light source, precise photo-electro-thermal (PET) multi-physics analyzing is also necessary for its reliability prediction [17,18]. Lots of works and models are used to optimize LED light source input currents, heat sink size, and shape [19–21]. In these models, fixed electro-photo transfer efficiency ($\eta_{E\text{-}P}$) is used (as shown in Formula 2).

Fig. 2 shows a LED chip normalized light output efficiency drop down to 60%. The relationship between the normalized light output and working hours (lifetime) can be expressed by the function (1).

$$\phi(\mathrm{t}) = \phi_0 e^{k\cdot t} \tag{1}$$

ϕ_0 is the initial value, t is the hours and k is the proportional coefficient. The value of the k is related to many parameters. These parameters affect the lifetime of the LED (as shown in Fig. 3).

As a conclusion, to describe the relations between these parameters are quite difficult. Especially in a Finite element method (FEM) model, the complex multi-physics coupling typically has a huge overhead in terms of computational resource [22,23]. And the multi-chip LED light source light output maintenance is a time related dynamic model, which also takes a difficulty to the LED reliability simulation.

In this paper, convenient and precise artificial neural networks (ANN) are used to overcome the abovementioned shortcomings. The

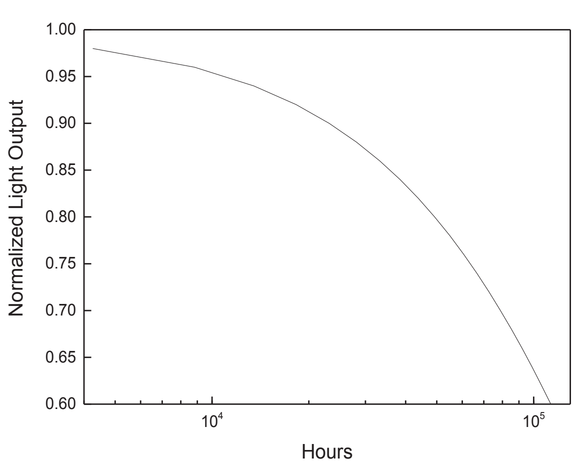

Fig. 2. The relationship between the normalized light output and working hours.

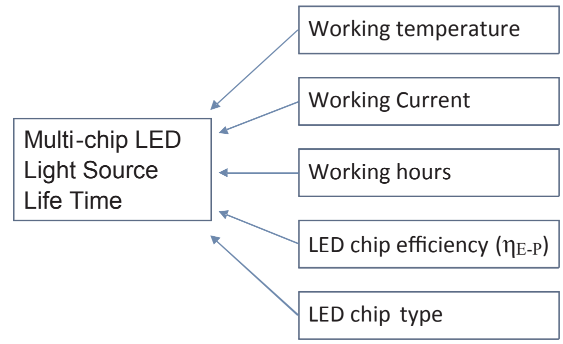

Fig. 3. Parameters affecting multi-chip LED light source lifetime.

ANN is an efficient solution to deal with a complex situation without a priori knowledge of the governing mathematical equations [24]. It can be viewed as a general, parameterized, nonlinear mapping between input and output variables.

To begin with, a PET ANN [25–27] is used to simplify the multi-physics coupling problem and the exact temperature distribution is simulated by FEM method in a multi-chip LED light source. Then, the input of lifetime ANN is the temperature of a single LED and the output is light output maintenance at different lifetime. The statics of the lifetime ANN outputs of all chips show the multi-chip light source light output maintenance.

In our work, a 40 LED chips high power road lamp light source is employed as a research sample. The LED chips are Philips LUXEON 3030-2D model. It is worth mentioning that any other type of LED can use this method.

LED PET ANN is trained by LUXEON 3030-2D chip PET measurement data. Lifetime ANN is trained by LUXEON 3030-2D LM-80 and TM-21 testing data. With the help of these two ANNs, time-consuming LM-80 life testing of multi-chip light source and the associated complex PET calculation can be avoided.

Single LED chip photo-electro-thermal (PET) ANN training

In the multi-chip high-power light source, the chip working temperature varies from each other. Accurate temperature description of a light source is critical for lifetime analyzes, and FEM calculation is an effective tool.

However, the light source temperature distribution is based on LED heat power consumption (Q).

$$Q(T) = \frac{P_E(T) - P_L(T)}{Vol} \tag{2}$$

$$P_L(T) = \eta_{E-P} \times P_E(T) \tag{3}$$

P_E is LED chip electro power and P_L is LED chip luminous power. They are all temperature (T) related parameters. To get temperature distribution of LED light source based on FEM calculation, PET coupling must be considered, which is difficult to deal with and lots of computing resource will be occupied.

To avoid complicated multi-physics coupling problem in the FEM temperature analyzing, the PET ANN adopted in our earlier work [25] is used to predict the LED chips real-time power consumption Q, P_E, *and* P_L.

A three-layer PET ANN (Fig. 4) is employed in this paper. There are 2 input layer neurons, 10 hidden layer neurons and 3 output layer neurons. The PET ANN input is LED chip driving current (I) and working temperature (T). The hidden layer input $h_j (j = 1,2\ldots,10)$ is decided by input layer weight parameter $w_{ij}^{(1)}(i = 1, 2, j = 1, 2, \cdots, 10)$and thresholds value $\mathrm{w}_{0\mathrm{j}}^{(1)}(\mathrm{j} = 1, 2\cdots10)$ $w_{0j}^{(1)}(j = 1, 2, \cdots, 10)$.$g_k(k = 1, 2, 3)$ is the hidden layer output.

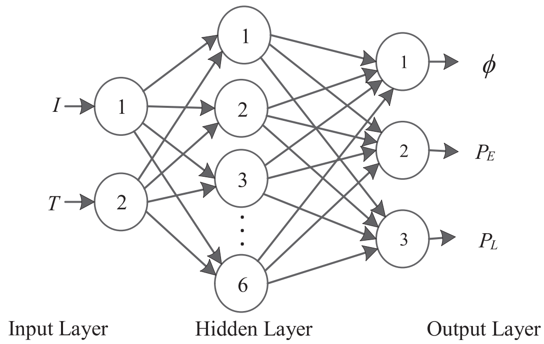

Fig. 4. A schematic of three-layer LED PET ANN.

$$h_j = w_{1j}^{(1)} I + w_{2j}^{(1)} T + w_{0j}^{(1)} \tag{4}$$

$$g_k = \sum_{j=1}^{10} \omega_{jk}^{(2)} \gamma(h_i) + \omega_{0k}^{(2)} \tag{5}$$

$g_k (k = 1, 2, 3)$ is the hidden layer output the $\gamma(.)$ is a hyperbolic tangent function, act as ANN neuron activation function. $w_{jk}^{(2)} (j = 1, 2, \cdots, 10, k = 1, 2, 3)$ is hidden layer weight parameter. $w_{0k}^{(2)} (k = 1, 2, 3)$ is thresholds value.

The PET ANN output is $y_k (k = 1, 2, 3)$, which is corresponds to the LED chip light output (ϕ), electro power (P_E) and luminous power (P_L).

$$y_k = \delta(g_k) = \delta(w_{jk}^{(2)} \gamma(h_j) + w_{0k}^{(2)}) \tag{6}$$

PET ANN can give any ϕ, P_E and P_L at different input currents I and working temperature T as long as the $w_{ij}^{(1)}$, $w_{0j}^{(1)}$, $w_{jk}^{(2)}$ and $w_{0k}^{(2)}$ matrix are trained in an acceptable error. The PET ANN is trained by LUXEON 3030-2D PET experiment data which weights and thresholds matrix in Table 1. $w_{01}^{(2)}$, $w_{02}^{(2)}$ and $w_{03}^{(2)}$ *are the* thresholds values of *the* ϕ, P_E and P_L respectively and every one of them is corresponding to the all hidden layers (Function 5). The trained result is shown n Fig. 5, the LED chip input current range is 0–450 mA and working temperature range is 280 K–390 K.

Predicted P_E, P_L are used to indicate LED heat consumption Q (function 2). The error between PET ANN output and verify data is 10^{-4}.

Without the complicate multi-physic operation, the PET ANN results can be called directly by FEM program. This can bring remarkable convenience to the PET temperature analyzing.

Single LED chip life-time ANN training

LED light output maintenance L_X is defined as $X\%$ (*usually X set as 70%*) light output power maintaining, which is a temperature related parameter and the testing time is 6000 h at least. It is a time-consuming work. Therefore, the LED light output maintenance test is only operated at 3 temperature points according to LM-80 standards. Table 2 gives Luxeon 3030-2D LED chip light output maintenance in 9000 h testing time. 150 mA is the typical work current of the Luxeon 3030-2D.

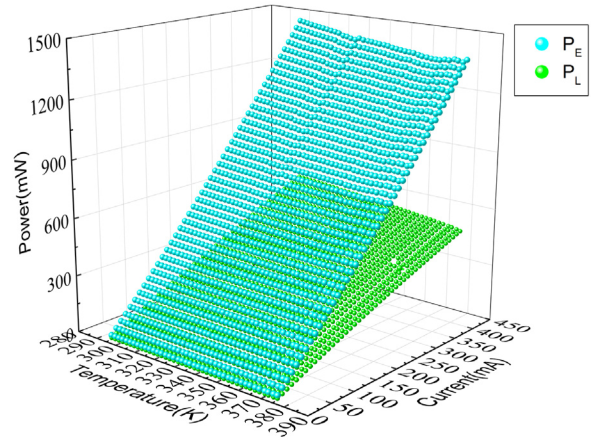

Fig. 5. LUXEON 3030-2D LED chip PET ANN training data.

At different working condition, the chip temperature varies from each other in the multichip light source. 3 temperature points are not enough to describe the working lifetime. And 9000 h testing time is too short to describe nearly 105 h. While lifetime ANN can give LED chip lifetime data at a large range of temperature by ANN training.

LED chip Lifetime ANN training data acquiring

Lifetime ANN is critical to LED chip reliability prediction and obtaining adequate credible training data is a key issue. But the LM-80 light output maintenance test data in Table 2 for the LUXEON 3030-2D LED only have 3 temperature points 328 K, 358 K, and 378 K in 9000 h.

For more reliable lifetime ANN training data, TM_{21} extrapolations [3] are employed to expand LM80 test data in this work.

First, curve fitting at 328 K, 358 K, and 378 K in Table 2 is conducted to describe the light output maintenance using the expression (7).

$$\phi(t) = \exp(-\alpha t^{\beta}) \tag{7}$$

where t is working hours of LED, $\phi(t)$ is the average normalized light output when LED's lifetime is t, α is a decay rate constant and β is a shape parameter.

Based on the Arrhenius equation, the LED light output maintain decay rate constant α at temperature *Ts* can be described as

$$\alpha = C \exp\left(-\frac{E_a}{k_B T_S}\right) \tag{8}$$

where$E_a$represents the activation energy, i.e. it is an index that reflects

Table 1
Matrices of weights and thresholds of led pet ann.

Hidden layer neurons (j = 1 ~ 10)	Input layer variables (i = 1,2)			Output layer variables (k = 1,2,3)					
	$W_{1j}^{(1)}$	$W_{2j}^{(1)}$	$W_{0j}^{(1)}$	$W_{j1}^{(2)}$	$W_{j2}^{(2)}$	$W_{j3}^{(2)}$	$W^{(2)}_{01}$	$W^{(2)}_{02}$	$W^{(2)}_{03}$
1	11.26	−13.28	−8.82	−0.14	−0.17	−0.16	0.053	0.063	0.063
2	8.77	13.55	−20.7	0.095	0.008	0.012			
3	−11.13	13.71	4.121	0.021	0.038	0.039			
4	16.85	−0.745	−10.8	−0.11	−0.13	−0.13			
5	3.2	14.48	−13.3	0.362	0.298	0.305			
6	−11.49	−13.52	9.87	−0.18	−0.21	−0.21			
7	−16.72	−4.42	7.487	0.158	0.178	0.174			
8	2.73	14.57	−8.01	0.264	0.234	0.237			
9	15.25	9.35	−4.47	−0.43	−0.51	−0.50			
10	10.64	12.43	−4.21	0.672	0.795	0.784			

Table 2
Luxeon 3030 2D LM-80 light output maintenance at input current 150 mA.

Life time (h)	1000	2000	3000	4000	5000	6000	7000	8000	9000
Ts = Tair = 378 K	0.9985	0.9932	0.9859	0.9758	0.9669	0.9538	0.9565	0.9492	0.9424
Ts = Tair = 358 K	0.9985	0.9942	0.9882	0.98	0.9724	0.9616	0.9624	0.9564	0.9499
Ts = Tair = 328 K	0.9996	0.9957	0.9903	0.9831	0.9763	0.9688	0.9692	0.9644	0.9594

the effect of temperature stress on the lifetime of the product, k_B is Boltzmann's constant.

For the same failure mechanism, C and E_a/k_B can be regarded as undetermined constants. These constants can be calculated by Eq. (9):

$$\begin{cases} \alpha_1 = Ce^{-\frac{E_a}{k_B T_{S1}}} \\ \alpha_2 = Ce^{-\frac{E_a}{k_B T_{S2}}} \end{cases} \tag{9}$$

where α_1 is the decay rate constant at temperature T_{S1}, and$\alpha_2$is the decay rate constant at temperature T_{S2}. The decay rate constant$\alpha_3$at temperature T_{S3} can be calculated by Eq. (10):

$$\alpha_3 = Ce^{-\frac{E_a}{k_B T_{S3}}} \tag{10}$$

β_3 in (11) is calculated by β_1 and β_2 mean square root as follows:

$$\beta_3 = \sqrt{\beta_1 \cdot \beta_2} \tag{11}$$

Based on expression (10) and (11), the different temperature coefficients are given in Table 3.

Finally, with parameters α and β, the LED lifetimes at different temperatures based on formula (12) are given in Table 4; γ is the normalized light output decay from 1 to 0.7.

L_{70} indicates that the normalized LED light output $\varphi(t)$ drops down to $\gamma = 0.7$.

$$t = \frac{\ln(\beta/\gamma)}{\alpha} \tag{12}$$

LED chip life-time ANN training and predicting results

A three-layer lifetime ANN (Fig. 6) was trained with the data in Table 4 with the method in part II. The life-time ANN input is temperature (T), the output is working hours (t, *hour*) and light output maintenance (L_X).

The training data giving by function (11) in Table 4 only have 11 temperature points. But after ANN training, the lifetime ANN can predict Luxeon 3030-2D chip lifetime at any temperature between 328 K and 378 K. There is no repeated calculation needed anymore.

It is the biggest advantage of life-time ANN over the curve fitting method. Especially in multi-chip system analyzing, Lifetime ANN will reduce the computation burden greatly.

Fig. 7 shows the lifetime ANN predicted Luxeon 3030 2D light output maintenance at 328 K and 150 mA input current. The solid line in the figure shows the fitting curve obtained according to the LED life test result at 328 K, and the scatter circle figure shows the prediction result of the lifetime ANN.

Table 3
light output maintenance temperature coefficient α and β for Luxeon 3030-2D.

Temperature	α (s^{-1})	β
328 K	4.5102×10^{-6}	0.9990
333 K	4.7217×10^{-6}	0.9993
338 K	4.9363×10^{-6}	0.9996
343 K	5.1676×10^{-6}	1.0
348 K	5.3749×10^{-6}	1.0001
353 K	5.5843×10^{-6}	1.0002
358 K	5.8536×10^{-6}	1.0011
363 K	6.0089×10^{-6}	1.0004
368 K	6.1639×10^{-6}	0.9998
373 K	6.3186×10^{-6}	0.9991
378 K	6.4729×10^{-6}	0.9985

In the 20 sets of forecast data given in the figure, the maximum error is 5.09% and the minimum is 0.1%. The correlation coefficient between the lifetime ANN and training data is 0.99715. The result shows that the trained artificial neural network prediction results are reliable.

Multi-chip LED light source temperature distribution analysis and lifetime prediction

Multi-chip PET and life-time ANN prediction

Part II and III show single LED chip PET ANN and lifetime ANN training. Based on LED PET ANN, the temperature distribution of multi-chip LED light source can be calculated using FEM. Thereby the lifetime of single-chip LED can be predicted by lifetime ANN, and then the statistic of all LED chips light output maintenance can be as a multi-chip light source lifetime at L_x working hours.

In this paper, the multichip light source is fabricated by the same type LED chip (LUXEON 3030-2D). And several types LED chip fabricated light sources would be also suitable in this work if the LED chip ANN is well trained.

The procedure for temperature and lifetime analysis of multi-chip light source is shown in Fig. 8. $\text{LED}_1 \sim \text{LED}_n$ are LED chips in multi-chip light source. Single LED chip ($\text{LED}_1 \sim \text{LED}_n$) operating under different input currents $I_{(1\sim n)}$ and temperatures $T_{(1\sim n)}$ result in an increase in the light source temperature. $I_{(1\sim n)}$ and $T_{(1\sim n)}$ are the well-trained PET $\text{ANN}_{(1\sim n)}$ input parameters. PET ANN predicts LED's heat consumption Q *(function 2 in part I)*. Every LED $Q_{(1\sim n)}$ will set as a heat source in the FEM temperature analyzing. Then, FEM calculation can be run to show the multi-chip light source temperature. Every LED temperature (T) feedbacks to the PET ANN, then PET ANN can give a new LED heat consumption Q. To obtain the light source temperature distribution, this loop will be terminated at a steady state. There is no complex photo-electro-thermal physical field computation in this procedure.

After getting the temperature of every LED chip in the FEM analyzing, these accurate temperature T values for the LED chip serve as inputs to the lifetime $\text{ANN}_{(1\sim n)}$. A single LED's lifetime and light output maintenance are predicted using the lifetime ANN (in part II).

The LED light output maintenance $L_{x(1\sim n)}$ decline at $t_{(1\sim n)}$ hours cause power consumption Q increasing, so life-time $\text{ANN}_{(1\sim n)}$ light output maintenance $L_{x(1\sim n)}$ will feedback to the FEM temperature analyzing. It is a time related dynamic analyzing.

Finally, light output maintenance of a multi-chip LED light source can be obtained from the output statistics of the lifetime $\text{ANN}_{(1\sim n)}$ at different chip's temperature.

Through this method, the lifetime of multi-chip LED light source is calculated from the exact value of each LED chip. Comparing with the method using one type LED in single temperature to predicting the light source lifetime, multi-chip LED light source lifetime prediction accuracy is improved. Most of all, for multi-chip light source, the unacceptable 6000 h test time is saved.

Table 4
Led chip lifetime (hours) of light output maintenance from 328 K to 378 K (Luxeon 3030 2D at 150 mA input current).

Life time maintenance	328 K	333 K	338 K	343 K	348 K	353 K	358 K	363 K	368 K	373 K	378 K
L98	4258	4128	4006	3919	3787	3662	3639	3437	3245	3063	2889
L96	8829	8495	8183	7909	7623	7355	7162	6868	6590	6326	6075
L94	13,497	12,954	12,448	11,983	11,540	11,125	10,758	10,372	10,006	9658	9327
L92	18,266	17,508	16,805	16,145	15,541	14,976	14,432	13,951	13,495	13,062	12,650
L90	23,139	22,163	21,257	20,398	19,630	18,912	18,187	17,609	17,061	16,540	16,045
L88	28,121	26,923	25,810	24,747	23,811	22,936	22,026	21,349	20,707	20,097	19,517
L86	33,219	31,792	30,467	29,196	28,089	27,053	25,954	25,175	24,436	23,735	23,069
L84	38,436	36,775	35,234	33,750	32,466	31,267	29,973	29,091	28,254	27,459	26,704
L82	43,779	41,879	40,115	38,413	36,950	35,582	34,090	33,101	32,163	31,273	30,427
L80	49,253	47,108	45,118	43,191	41,544	40,004	38,309	37,210	36,169	35,181	34,242
L78	54,867	52,470	50,246	48,091	46,254	44,538	42,634	41,424	40,277	39,188	38,153
L76	60,626	57,972	55,509	53,117	51,087	49,189	47,071	45,747	44,491	43,299	42,166
L74	66,539	63,619	60,911	58,278	56,049	53,965	51,627	50,185	48,817	47,519	46,286
L72	72,614	69,423	66,461	63,580	61,146	58,871	56,308	54,745	53,262	51,856	50,519
L70	78,860	75,389	72,168	69,032	66,388	63,916	61,120	59,433	57,833	56,314	54,871

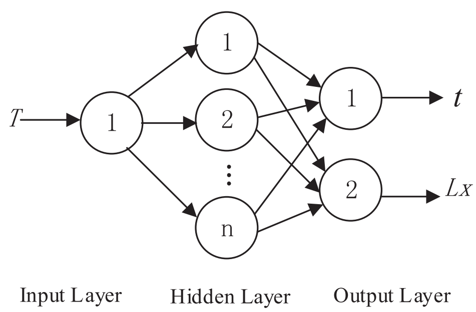

Fig. 6. A schematic of three-layer life time ANN.

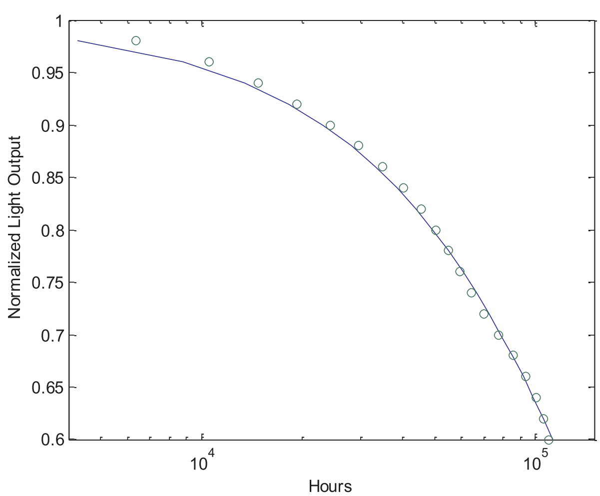

Fig. 7. Luxeon 3030-2D predicted (circles) and expected (solid line) light output at different working hours at 328 K and 150 mA input current.

ANN predicted Multi-chip lifetime results and analyzing

As a general example, a multi-chip LED road lamp light source is used to analyze the temperature and lifetime characteristics. The light source has 40 LUXEON 3030-2D LED chips, an aluminum fin heat sink and an epoxy resin lens covering on the LED chips (Fig. 1).

With the help of PET ANN, the final FEM temperature distribution is shown in Fig. 9(a). Compared with the test results in Fig. 9(b), the computing error can be controlled within 2 °C.

In this work, every LED chip works at 150 mA and the environmental temperature is typically 21.1 °C. As a benefit of the excellent heat sink design, LED chip temperature difference in the light source is only 5.09 °C. However, after thousands of working hours, the lifetime ANN $_{(1\sim40)}$ output values vary.

In the road lamp, the lifetime ANN can predict every LED chip light output maintenance curve at a different temperature. In Fig. 10, the normalized LED light output curve, at a maximum LED temperature of 61.45 °C and a minimum LED temperature of 56.36 °C, are given. The lifetime of a LED chip L_{70} at maximum temperature is 72,486 h; at minimum temperature, it is 75,583 h. Thus, the gap in the lifetime prediction is 3097 h. As for L_{60}, the lifetime gap is 3230 h. But any value in the lifetime gap is not accurate for multi-chip light source lifetime prediction.

However, the exact value of light source lifetime could be given using all 40 LED life-time ANNs' prediction curves. The multi-chip light source light output maintenance ($L_{x\text{-}multichip}$) statics is given by (function 13).

$$\frac{\sum_{i=1}^{n}\phi_i(T_i,\,t)}{\sum_{i=1}^{n}\phi_i(initial)} = L_{X\text{ - multichip}} \tag{13}$$

$\phi_i(initial)$ is the original light output for a single LED, n is the LED number of the light source (n = 40 in this part), $\phi_i\ (T_i,t)$ is the maintenance for a single LED light output at T_i temperature and t is the working time or lifetime in hours.

For example, if we set $L_{x\text{-}multichip} = 0.7$, the multichip light source normalized light output is $\sum_{i=1}^{40}\phi_i(initial) = 1$. The multi-chip light source L_{70} lifetime t can be found in the lifetime ANN output data matrix, the 40 life-time ANNs output $\varphi_i(T_i,t)$ should be satisfied:

$$\sum_{i=1}^{40}\phi_i(T_i,\,t) = 0.7 \tag{14}$$

If we set function (13) in lifetime ANN$_{(1\sim40)}$ light output curve cluster in Fig. 11, the multichip light source lifetime t can be found by the sum of φ_n (function 14).

With this method, the road lamp light source lifetime is L_{70} = 73,518 h and L_{60} = 109,080 h. Benefit from a good heat sink design, the temperature difference is only 5.09 °C in the road lamp module. The multi-chip light source lifetime difference is not obvious between the maximum and minimum temperature.

For L_{70} lifetime prediction, the exact value is given by function (13, 14) differs from the maximum temperature lifetime (72,486 h) by 1032 h and from the minimum temperature lifetime (75,583 h) by 2065 h. In the high-temperature difference light source, the lifetime prediction difference between maximum and minimum is large. And the advantage of this method in function (13, 14) will be more distinct.

In conclusion, the multi-chip light source lifetime results predicted using the lifetime ANNs can be given precisely. It will give a reliable approach to evaluate LED heat sink and optical design.

All the hours of this work including the experiment to collect ANN training data, the FEM and ANN model build and calculation used

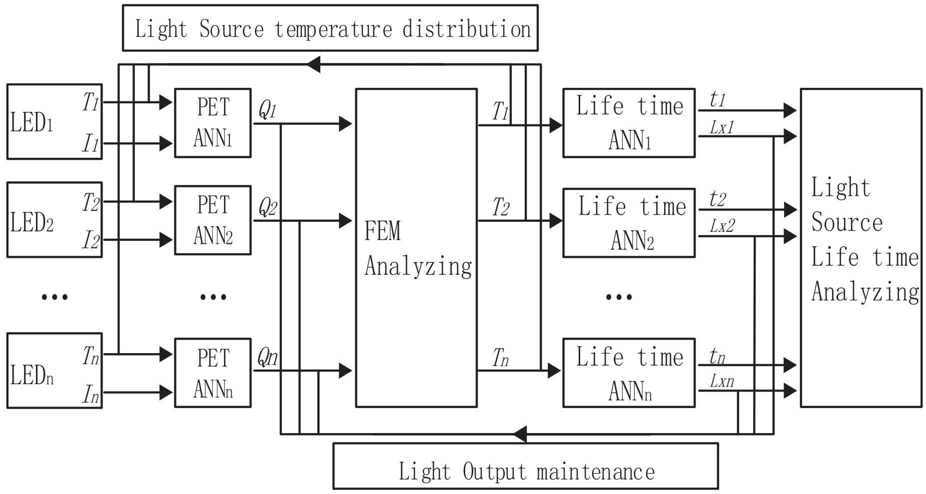

Fig. 8. LED light source lifetime prediction with PET and lifetime ANN.

about 10 h. thousands of hours of testing time are avoided.

Conclusion and discussion

To predict LED light source reliability in a high-power solid-state lighting system, LED PET ANN and lifetime ANN are employed to decrease the simulation time and increase the precision of analysis.

The Philips LUXEON 3030-2D LED LM-80 test data and TM_{21} interpolation data are used to train the lifetime ANN. Then, the temperature distribution data of the multichip light source, which is given by PET ANN and FEM simulation, are entered the lifetime ANN to obtain LED lifetime prediction. The multi-physics PET ANN is trained by the PET measurements data, which is an efficient method to simplify multi-physics coupling problems. Computational resource and time are saved compared to solving numerical multi-physics equations.

Based on this method, every LED chip's lifetime, in a high-power lighting system, can be precisely described at different temperatures. The correlation coefficient between the lifetime ANN and training data is 0.99715; therefore, the predicted results based on the ANN method are credible. The statistics of all LED chips' lifetime indicate the reliability of a multichip light source. This method is more accurate compared to the results of a single temperature lifetime prediction.

All the above-mentioned procedures can be conducted, with adequate training data from the whole LED lighting system, in a single ANN. However, combining PET ANN and lifetime ANN is an efficient and effective method to predict system reliability. In this study, PET ANN and lifetime ANN are trained by LED chip characteristics data, rather than the lighting source data. In other words, the two-level ANNs in this work are the descriptions of a given LED chip's characteristics. Any lighting source with this LED chip, no matter a road lamp or a spotlight, can be predicted by these two ANNs and a FEM simulation.

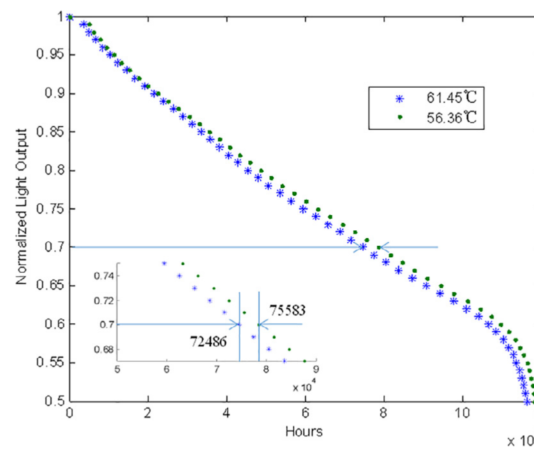

Fig. 10. LED chip light output and life prediction curve with a life-time ANN at the maximum and minimum temperature.

This approach will present a great advantage, and convenience, to the heatsink and system reliability design works concerning an LED multichip light source.

In this paper, the lifetime ANN temperature inputs—decided by the LM-80 test data and TM_{21} extrapolation—range from 328 K to 378 K. This range is adequate to represent the working condition of a lighting system. For some extremely low or high-temperature applications, extra temperature lifetime for an LED chip must be extrapolated using the TM_{21} method. However, the confidence level of lifetime prediction results that are based on such extrapolation will be low.

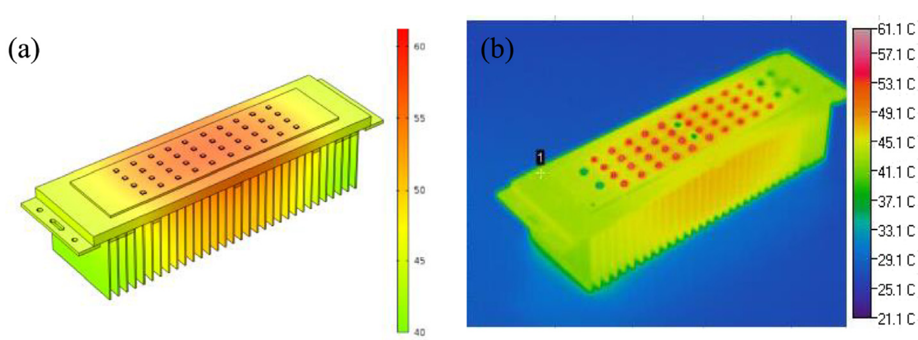

Fig. 9. (a) FEM Calculated LED road lamp light source module with 40 LEDs temperature results with PET ANN (b) Tested temperature distribution.

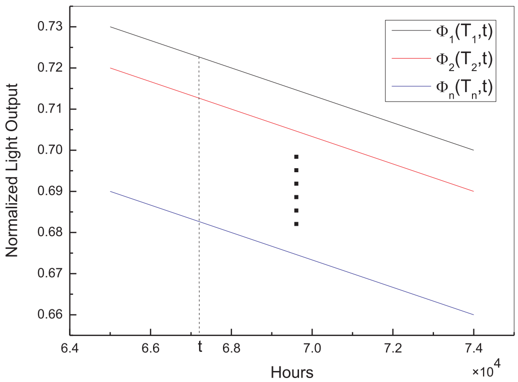

Fig. 11. Multi-chip light source lifetime (t) statics with life-time ANNs' prediction curve.

Acknowledgements

Scientific research program of Tianjin Education Committee (2017ZD06); Program for innovation team of Tianjin Institution of Higher Learning, China (TD13-5035); National Natural Science Foundation of China (61575144, 61504093); Science and Technology Project of Tianjin (16YFXTGX00230).

References

[1] IES Approved method for measuring lumen maintenance of LED light sources. ISBN No.978-0-87995-227-3; 2008.
[2] IES TM-21-11: Projecting long term lumen maintenance of LED light sources.
[3] Wang X, Qian K. A fast method for lifetime estimation of blue light-emitting diode chips based on nonradiative recombination defects. IEEE Photon J 2017;99. 1-1.
[4] Huang S, et al. A novel multiple-stress-based predictive model of LEDs for rapid lifetime estimation. Microelectron Reliab 2017;78:46–52.
[5] Ruknudeen Fazludeen, Asokan S. Application of particle filter to on-board life estimation of LED lights. IEEE Photon J 2017;9(3):1–16.
[6] Qian C, et al. Photometric and colorimetric assessment of LED chip scale packages by using a step-stress accelerated degradation test (SSADT) method. Materials 2017;10(10):1181.
[7] Xiao J, et al. Multichannel online lifetime accelerating and Testing system for power light-emitting diodes. IEEE Photon J 2017;99. 1-1.
[8] Qu X, et al. A lifetime prediction method for LEDs considering mission profiles. Appl Power Electron Conf Expos IEEE 2016.
[9] Yan Q. Reliability prediction of the high-powered LED based on dynamic neural network. Proceedings of First International Conference on Electronics Instrumentation & Information Systems (EIIS). 2017. p. 1–3.
[10] Padmasali A, Kini S. Prognostic "algorithms for L70 life prediction of solid state lighting". Light Res Technol 2015;48(5):608–23.
[11] Zhang J, et al. An optimized model for lifetime prediction of LED-based light bars using luminance degradation method. Light Res Technol 2016;50:316–25.
[12] Qian C, et al. An accelerated test method of luminous flux depreciation for LED luminaires and lamps. Reliab Eng Syst Saf 2016;147:84–92.
[13] Davis J, et al. Lifetime predictions for dimmable two-channel tunable white luminaires. Therm Thermomech PhenomElectron Syst IEEE 2017:1049–55.
[14] Perpina X, et al. Thermal analysis of LED lamps for optimal driver integration. IEEE Trans Power Electr Jul. 2015;30(7):3876–91.
[15] Sun L, et al. Simulation and evaluation of the peak temperature in LED light bulb heatsink. Microelectron Reliab Jun. 2016;61:140–4.
[16] Poppe A. Simulation of LED based luminaires by using multi-domain compact models of LEDs and compact thermal models of their thermal environment. Microelectron Reliab 2017;72:65–74.
[17] Kabi H, et al. Smart modeling of microwave devices. IEEE Microw Magn May 2010;11(3):105–18.
[18] Zhang QJ, Gupta KC. ANNs for RF and microwave design. Boston. IEEE Trans Microw Theory Technol Apr. 2003;51(4):1339–50.
[19] Ma X, et al. Design of the optical structure of a LED light of airfield used on the taxiway centerline of bend. International Symposium on Photonics and Optoelectronics International Society for Optics and Photonics. 2014. 92331R.
[20] Paul B, et al. Modelling and thermal analysis of honey comb heat sink for LEDs in street lighting applications. IEEE International Conference on Inventive Systems and Control IEEE. 2017. (youhua sink).
[21] Tian C, et al. Thermal analysis and an improved heat-dissipation structure design for an AlGaInP-LED micro-array device. Optoelectron Lett 2017;13(4):282–6.
[22] Li J, et al. Analysis of thermal field on integrated LED light source based on COMSOL multi-physics finite element simulation. Phys Procedia Jan. 2011;22:150–6.
[23] Ionescu C, et al. Simulation of printed thermoelectric generators using finite element analysis. Proc. IEEE 17th Int. Symp. Design Technol. Electron. Packag. 2011. p. 436–41.
[24] Sun Y, Guo G. Application of artificial neural network on prediction reservoir sensitivity. Proc. Int. Conf. Mach. Learn Cybern. 2005. p. 4770–3.
[25] Liu H, et al. High-power LED photoelectrothermal analysis based on back-propagation artificial neural networks. IEEE Trans Electron Dev 2017;72:65–74.
[26] Zhang QJ, et al. Artificial neural networks for RF and microwave design-from theory to practice. IEEE Trans Microw Theory 2003;51(4):1339–50.
[27] Zhang R, et al. Global convergence of online bp training with dynamic learning rate. IEEE Trans Neur Net Lear Feb. 2012;23(2):330–41.

Hongwei Liu received the B.Eng. And M.Sc.Eng. degrees from Tianjin Polytechnic University (TJPU), Tianjin, China, and the Ph.D. degree from the Institute of semiconductor, Chinese Academy of Sciences, Beijing, China. He is currently a Professor with the School of Electronics and Information Engineering, TJPU, and also with the Tianjin Key Laboratory of Optoelectronic Detection Technology and System, Tianjin.

Dandan Yu was born in China in 1994. She is currently pursuing the Degree in reading with Tianjin Polytechnic University, Tianjin, China. Her mentor is H. Liu. Her current research interests include the enhanced LED luminescence by surface plasmon.