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Lumen degradation analysis of LED lamps based on the subsystem isolation method

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The lumen degradation of LED lamps undergoing an accelerated aging test is investigated. The entire LED lamp is divided into three subsystems, namely, driver, lampshade, and LED light source. The parameters of output power [Watts (W)], transmittance (%), and lumen flux (lm) are adopted in the analysis of the degradation of the driver, lampshade, and LED light source, respectively. Two groups of LED lamps are aged under the ambient temperatures of 25°C and 85°C, respectively, with the aging time of 2000 h. The lumen degradation of the lamps is from 3.8% to 4.9% for the group under a temperature of 25°C and from 10.6% to 12.7% for the group under a temperature of 85°C. The LED light source is the most aggressive part of the three subsystems, which accounts for 70.5% of the lumen degradation of the LED lamp on average. The lampshade is the second degradation source, which causes 21.5% of the total amount on average. The driver is the third degradation source, which causes 6.5% under 25°C and 2.8% under 85°C of the total amount on average.

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1. INTRODUCTION

Recently, white LEDs converted by blue chip and yellow phosphor have been developed owing to their high efficiency, environmental benefits, and long lifetime [1–3]. To verify the long-lifetime performance, Energy Star proposed a well-known 6000 h test for the LED light source [4], as well as the LED lamps [5]. The LED lifetime of $L_{70\%}$, defined as the time for luminous maintenance to drop to 70%, could be predicted by TM-21-11 [6] with the lumen degradation acquired in the 6000 h test. However, 6000 h is not a long enough period to catch up with the present LED production, and therefore the thermal stress is always applied in the LED accelerated aging test to shorten the test time in most studies [7–11].

The failure mechanism analysis and the lifetime prediction for LED lamps under accelerated aging tests remain challenging tasks. First, there are various unexpected failure modes at the system level under different stress levels [12,13]. Second, the lifetime spans of the subsystems always differ greatly, which makes the lifetime of the LED lamp limited to the worst subsystem.

In recent years, some researchers [14,15] divided the LED lamp into several subsystems, which are the driver, the LED light source, and the lampshade and fixture. The analysis for the different subsystems is conducted. For the LED light source, studies [16–20] focused on the reliability tests and lifetime prediction of LED packages/modules. Yoon *et al.* [21] made a comparison between LED packages and LED lamps in the reliability analysis. It was shown that the shape parameters of the Weibull distribution in the two cases were, respectively, 8.87–11.12 and 14.87–19.82, which means the failure mechanism was different. IES LM-82 [22] pointed out that the thermal condition of the LED light source should be considered when it was applied in a certain lighting system and different thermal conditions corresponding to different reliabilities. As a result, the lifetime of the LED lamp cannot be simply taken as that of the LED light source.

For the LED driver, De Santi *et al.* [23] indicated that the output power of the driver decreased over time, and one of the sample's power decreased by 5% after 2000 h aging under an ambient temperature of 40°C. Sun *et al.* [24] pointed out that the output power of the LED driver with isolated components decreased by the same rate in a 300 h aging test under ambient temperatures of 55°C and 105°C. Therefore, the decrease of the output power of the LED driver results in a decrease of the lumen flux of the LED lamp.

For the LED lampshade, mostly made of polymethyl methacrylate (PMMA), Lu *et al.* [25] investigated the failure mechanism of PMMA under different thermal stresses. The results showed that the transmittance of PMMA decreased significantly in the wavelength band from 380 nm to 730 nm, causing a 10.2% decrease of the lumen flux for 360 h of aging under an ambient temperature of 55°C. The degradation of the lampshade is the darkening of PMMA, which reduces the transmittance of PMMA and is therefore responsible for the decrease of the luminous flux as well as the color shift of the LED lamp.

The main purpose of this research is to investigate the degradation of each subsystem of the LED lamp, namely the driver, lampshade, and LED light source, under the thermal accelerated aging test. The variation in the output power (W) of the driver, the variation in transmittance (%) of the lampshade, and the variation in the lumen flux (lm) of the LED light source are taken as the parameters for evaluating the degradation of each subsystem. The proportion of lumen degradation of the LED lamp caused by each subsystem is given for comparison. The second purpose is to investigate the difference in the degradation of the subsystems under different thermal stress levels, and the normal temperature of 25°C and the elevated temperature of 85°C are applied in this research.

2. THEORETICAL ANALYSIS

The total lumen degradation of the LED lamp over time D_{all} is divided into the three parts D_1, D_2, and D_3, which are caused by the driver, the lampshade, and the LED light source, respectively, as given by

$$\Phi_0 - \Phi_t = D_{all} = D_1 + D_2 + D_3, \quad (1)$$

where Φ_0 is the initial lumen flux of the LED lamp before aging and Φ_t is the lumen flux after an aging time t.

For the LED driver, the correspondent lumen degradation of D_1 can be evaluated by the variation in its output power using

$$D_1 = (W_0 - W_t) \times \mu, \quad (2)$$

where W_0 and W_t are, respectively, the output power of the LED driver before and after t hours of aging and μ is the variation rate of the lumen flux of the LED light source with respect to the output power of the driver.

For the lampshade, the correspondent lumen degradation of D_2 is evaluated by the variation of the transmittance of $T(\lambda)$, which is given by

$$T(\lambda) = \mathrm{SPD}_1(\lambda)/\mathrm{SPD}_2(\lambda), \quad (3)$$

where $\mathrm{SPD}_1(\lambda)$ and $\mathrm{SPD}_2(\lambda)$ are the spectral power distribution (SPD) of the LED lamp with and without the lampshade, respectively. Then D_2 can be calculated by

$$D_2 = \int_{380}^{780} K_m \times (T_0(\lambda) - T_t(\lambda)) \times V(\lambda) \times \mathrm{SPD}_t \mathrm{d}\lambda, \quad (4)$$

where $T_0(\lambda)$ and $T_t(\lambda)$ are the transmittance of the lampshade before and after t hours of aging, respectively. K_m is 683 lm/W, $V(\lambda)$ is the vision function under photopic vision, and SPD_t is the spectral power distribution of the LED lamp without the lampshade after t hours of aging. The visible wavelength band from 380 nm to 780 nm is adopted.

For the LED light source, the correspondent lumen degradation of D_3 is evaluated by the degradation of the LED itself, which is expressed as

$$D_3 = \Phi_0' - \Phi_t', \quad (5)$$

where Φ_0' and Φ_t' are the lumen flux of the LED light source under the rated current before and after t hours of aging, respectively. With the acquired D_{all}, D_1, D_2, and D_3, the proportion of the lumen degradation of each subsystem is obtained and compared.

3. EXPERIMENTS

A. Test Samples

The subsystems of the driver, the lampshade, the LED light source, the heat sink, and the lampholder E27 of the tested LED lamp in this research are shown in Fig. 1. The driver is placed outside the LED lamp for the measurement of the output power. The main parameters of each subsystem are listed in Table 1.

Six LED lamps from the same batch are divided into two groups, with samples 1, 2, and 3 as the first group and samples 4, 5, and 6 as the second group. The samples in the first group are aged under the normal temperature of 25°C while the samples in the second group are aged under the elevated temperature of 85°C. The total aging time for both groups is 2000 h, and the parameters measurement for each subsystem is taken before and after the aging process.

B. Test for LED Lamp and Subsystems

The experimental apparatus is shown in Fig. 2. The LED lamp is fixed inside a temperature chamber, and outside the chamber

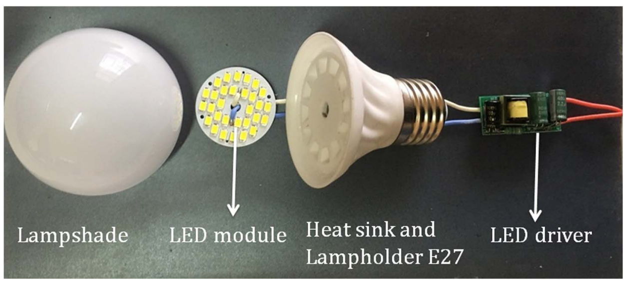

Fig. 1. Subsystems of the LED lamp.

Table 1. Main Parameters of Each Subsystem

	Composition	Thirty 0.15 W, GaN-Based White LEDs Converted by $Y_3Al_5O_{12}$:Ce
LED source	Rated input/output	135 mA (DC)/340 lm, 3500 K
Driver	Rated input/output	220V(AC)/135 mA (DC)
Lampshade	Material	PMMA
Heat sink	Material	Ceramics

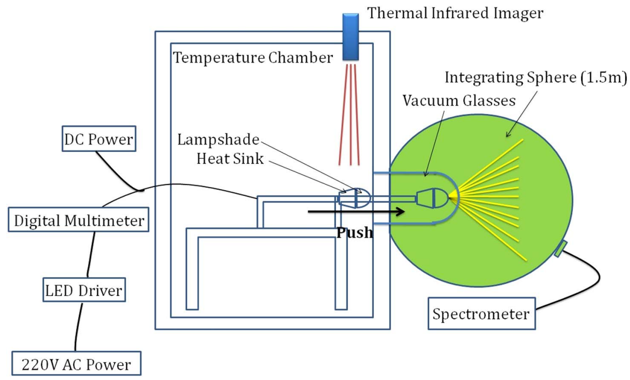

Fig. 2. Sketch map of the measurement system.

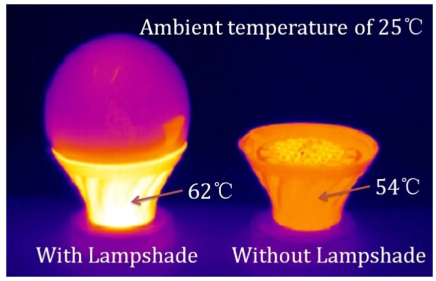

Fig. 3. Comparison of the infrared image of the LED lamp with lampshade and that without lampshade.

a 1.5 m integrating sphere connected to a spectrometer is used for the collection of optical parameters of the LED lamp. The side opening of the integrating sphere is closely connected to the window of the chamber. To achieve thermal isolation between the integrating sphere and the chamber, a special hood made of vacuum glasses is placed at the window.

By using this measurement system, the optical parameters of the LED lamp under different thermal conditions can be measured. First, different ambient temperatures are controlled by the chamber, and the correspondent thermal condition of the LED lamp is monitored by a thermal infrared imager fixed on the top of the chamber. Second, the lamp is pushed into the integrating sphere to ensure that the measurement is with highest lumen flux of the sample. Finally, the output of the LED lamp under a certain thermal condition is given by the spectrometer.

The measurement steps for the LED lamp, driver, lampshade, and LED light source are given as follows.

Step-1 for the LED lamp: The chamber temperature is controlled to 25°C, and therefore the samples in the second group after 2000 h of aging must be fully cooled down before testing. The tested sample is fixed inside the chamber and preheated for 20 min before the measurement. The LED driver is placed outside the chamber and powered by 220 V (AC). The lumen flux of Φ and the spectral power distribution of SPD_1 of LED lamp are then measured by the spectrometer.

Step-2 for the driver: During the optical parameter measurement in step-1, the stable output power (W) of the driver is simultaneously measured with a digital multimeter outside the chamber.

Step-3 for the lampshade: In the following steps, the lampshade is removed from the tested lamp, and thereby the thermal condition and the junction temperature of the LED lamp inevitably vary. Cai *et al.* [13] indicated that the variation in the temperature of the LED heat sink could be 8–10°C, before and after removing the lampshade. Figure 3 shows the comparison of the infrared image of the LED lamp with and without the lampshade, under the normal working conditions. Note that at the ambient temperature of 25°C, the heat sink temperature (T_H) of the LED lamp is 62°C in the case with the lampshade, and it is 54°C in the case without the lampshade. Therefore, when the lampshade is removed, the chamber temperature should be adjusted to ensure the T_H is unchanged. Then the sample is pushed into the integrating sphere, and the spectral power distribution of SPD_2 is given by the spectrometer. In our previous research in Ref. [20], the LED junction temperature measured by the forward voltage method shows an upward trend over the aging time, which gives a variation of about 6°C–8°C after 3000 h of aging under an ambient temperature of 80°C. Therefore, the thermal condition of the LED lamp should be tested and adjusted during the aging process. It is emphasized that the integrating sphere system should be re-calibrated with the auxiliary lamp before the measurement, due to the change of the tested target.

Step-4 for LED light source: The LED driver and AC power are substituted by a DC power, and the rated current of 135 mA (DC) is applied to the sample. The lampshade is removed, and the chamber temperature is adjusted as described in step-3. After 20 min preheating, the lumen flux of Φ' is measured. In this way the influence of the LED driver and the lampshade on the lumen degradation is excluded, and the variation of Φ' over 2000 h can be regarded as the degradation of the LED light source itself.

4. RESULTS AND ANALYSIS

A. Lumen Degradation of LED Lamp D_{all}

Figure 4 shows the difference of the lumen flux measured before and after 2000 h of aging for the six samples in step-1. Note that the degradation of D_{all} is 13.9 lm (4.5%), 11.9 lm (3.8%), 14.7 lm (4.9%), 38.4 lm (12.7%), 37.0 lm (11.8%),

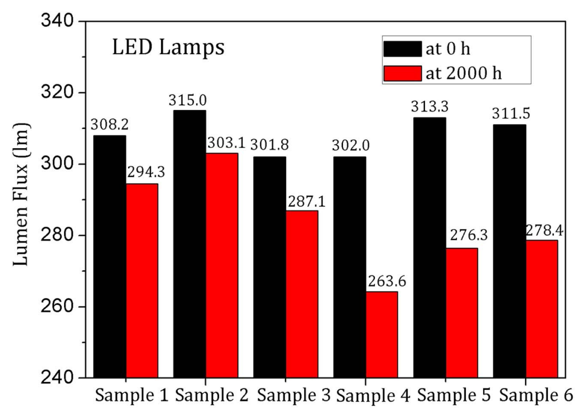

Fig. 4. Comparison of the lumen flux measured in Step-1 at 0 h and 2000 h.

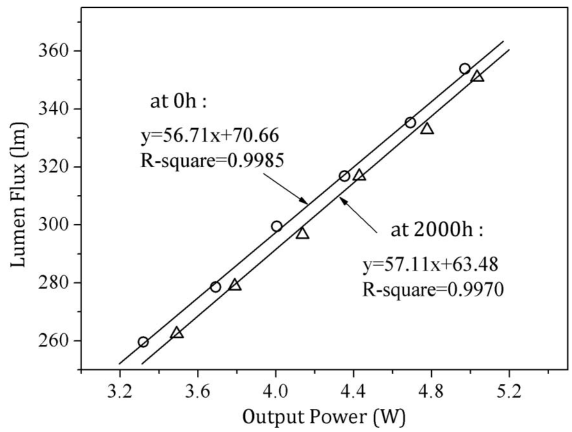

Fig. 5. Lumen flux as a function of output power for sample 1.

and 33.1 lm (10.6%), respectively, for the six samples after 2000 h of aging.

B. Lumen Degradation of Driver D_1

To evaluate the effect of the degradation of the driver on the lumen degradation of the LED lamp, the variation rate of the lumen flux of the LED light source with respect to the output power of the driver μ should be determined first. Figure 5 shows the experimental results of the lumen flux under different driver output power for sample 1, before and after 2000 h of aging. Note that the lumen flux can be linearly fitted for both cases with R-square (coefficient of multiple determination) higher than 0.99. The slope of the fitting for the data before aging is 56.71 (lm/W), and it is 57.11 (lm/W) for the data after 2000 h of aging. As a result, the average value of 56.91 is taken as the variation rate of μ for sample 1. The μ values for the other five samples are, respectively, 55.32, 57.66, 60.35, 59.62, and 55.30 (lm/W).

Table 2 lists the output power of the driver before and after the 2000 h of aging measured in step-2, and the decreased output power of ΔW for the six samples. Note that the decreased output power of the driver over 2000 h aging at a normal temperature of 25°C is 0.015 W on average, and it is 0.018 Wat elevated temperatures of 85°C. This indicates that an elevated temperature of 85°C has little effect on the degradation of the driver. With the decreased output power and the μ value, the lumen degradation of D_1 caused by the driver is calculated according to Eq. (2). The values of D_1 for the samples are listed in the last column of Table 2. Note that the averaged value of

Table 2. Degradation of Driver D_1

Aging Temperature (°C)		Power (W) at 0 h	Power (W) at 2000 h	Δ Power (W)	μ lm/W	D_1 lm
	No. 1	4.725	4.711	0.014	56.91	0.81
25	No. 2	4.635	4.620	0.015	55.32	0.83
	No. 3	4.821	4.804	0.017	57.66	0.98
	No. 4	4.748	4.548	0.020	60.35	1.20
85	No. 5	4.622	4.607	0.015	59.62	0.88
	No. 6	4.535	4.517	0.018	55.30	1.00

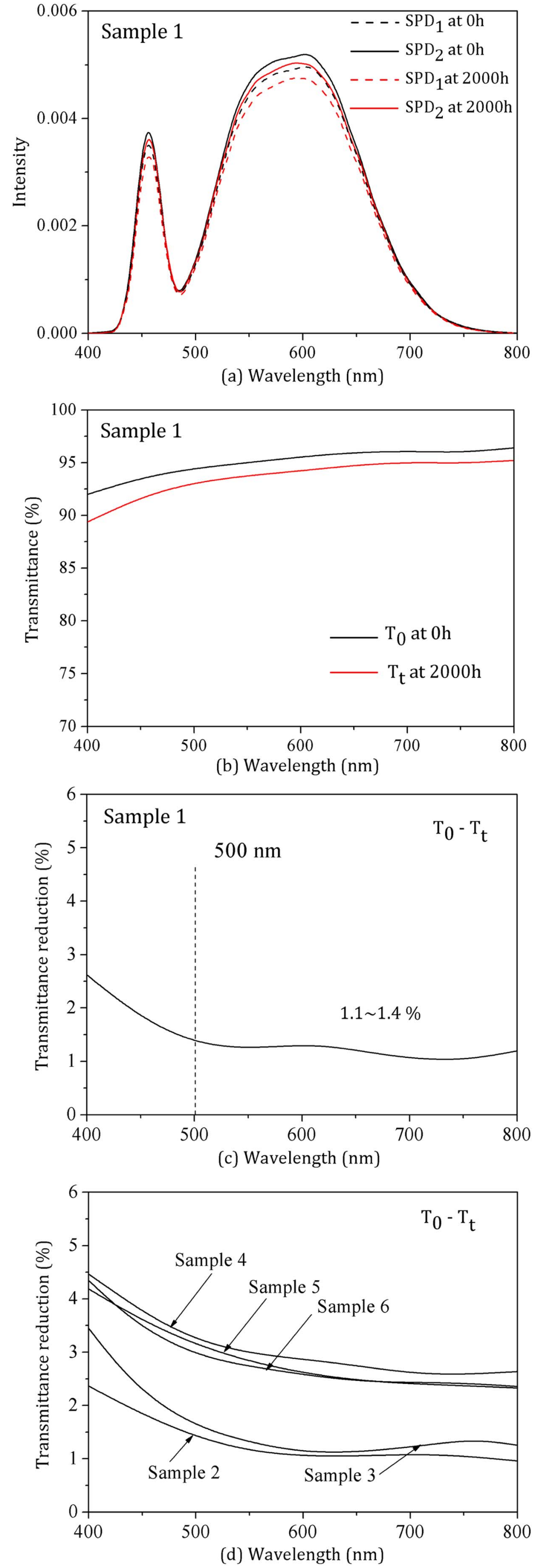

Fig. 6. (a) SPD_1 and SPD_2 of sample 1 at 0 h and 2000 h. (b) The transmittance of sample 1 at 0 h and 2000 h. (c) The transmittance reduction of sample 1 after 2000 h of aging. (d) The transmittance reduction of the other five samples.

D_1 is 0.87 lm for the samples aging at 25°C, and is 1.03 lm for the samples aging at 85°C.

C. Lumen Degradation of Lampshade D_2

To investigate the transmittance of the lampshade, the SPD_1 in step-1 and the SPD_2 in step-3 are compared. Figure 6(a) shows the SPD_1 and SPD_2 of sample 1 at 0 h and after 2000 h of aging, and Fig. 6(b) shows the calculated transmittance T_0 (before aging) and T_t (after 2000 h of aging) according to Eq. (3). Apparently, T_t is lower than T_0 at each wavelength over the visible band. The transmittance reduction ($T_0 - T_t$) is shown in Fig. 6(c). Note that as the wavelength increases, $T_0 - T_t$ decreases within the band from 400 nm to 500 nm and becomes steady with the value of 1.1–1.4% within the band from 500 nm to 800 nm. Figure 6(d) shows the calculated $T_0 - T_t$ for the other five samples. Note that the values of $T_0 - T_t$ are larger for the samples under an aging temperature of 85°C compared with those under 25°C, indicating that the degradation of the lampshade strongly correlates to the elevated temperature.

With the obtained T_0, T_t, and SPD_2 at 2000 h, the correspondent lumen degradation of D_2 caused by the lampshade is calculated according to Eq. (4). The values of D_2 are listed in Table 3, which are from 2.4 to 3.1 lm for samples 1, 2, and 3, and are from 7.6 to 8.1 lm for samples 4, 5, and 6.

D. Lumen Degradation of LED Light Source D_3

The lumen flux of the LED light sources of the sample is acquired in step-4. The values of Φ' (before aging) and Φ'_t (after 2000 h of aging) are listed in the third and fourth row, respectively, of Table 4. According to Eq. (5) the correspondent lumen degradations of D_3 are calculated and listed in the last row of Table 4. Note that the lumen degradation caused by the LED light source over 2000 h of aging at a normal temperature of 25°C is 9.3 lm on average, and it is 26.0 lm at an elevated temperature of 85°C. The latter is about 2.8 times larger than the former, implying that thermal stress plays an important role in the degradation of the LED light source.

Table 3. Degradation of Lampshade D_2

Aging Temperature (°C)		25			85	
No.	1	2	3	4	5	6
D_2 (lm)	3.0	2.4	3.1	8.1	7.6	7.6

Table 4. Degradation of LED Light Source D_3

Aging Temperature (°C)		25°C			85°C	
No.	1	2	3	4	5	6
Φ' at 0 h (lm)	335.2	342.5	338.0	339.3	341.8	336.4
Φ'_t at 2000 h (lm)	325.3	334.0	327.6	311.0	314.3	312.2
D_3 (lm)	9.6	8.3	10.1	27.6	26.8	23.6

E. Analysis of D_{all}, D_1, D_2, and D_3

For sample 1, the lumen degradation of the LED lamp of D_{all} is 13.9 lm after 2000 h of aging at a temperature of 25°C (see Fig. 4). The lumen degradation caused by the driver of D_1 is 0.81 lm (see Table 2), which accounts for 5.8% of D_{all}. The lumen degradation caused by the lampshade of D_2 is 3.0 lm (see Table 3), which accounts for 21.7% of D_{all}. The lumen degradation caused by the LED light source of D_3 is 9.6 lm (see Table 4), which accounts for 69.1% of D_{all}. It is noticed that the sum of D_1, D_2, and D_3 is 96.6% of D_{all}. The remaining 3.4% of the total lumen degradation is caused by the measurement errors and some interactions among each subsystem, which can result in a faster degradation of the whole LED lamp. For example, the lighting by the LED light source has a direct effect on the degradation of the lampshade, and the degradation of the light source therefore effects the degradation of the lampshade. However, the degradation value caused by this effect cannot be detected in step-3. Similar interactions among the three subsystems contribute to the remaining 3.4% of the total lumen degradation.

Table 5 lists the results for the six samples. These results show that the lumen degradation of the aged LED lamp is mainly due to the degradation of the LED light source, which causes about 70.5% of the total amount on average. The lampshade is the second degradation source, which causes about 21.3% of the total amount on average. The driver is the third degradation source, which causes about 6.5% (at a normal temperature of 25°C) and about 2.8% (at an elevated temperature of 85°C) of the total amount on average.

5. CONCLUSIONS

To investigate the degradation of each subsystem of the LED lamp in the aging test, the LED lamp is divided into the three subsystems of driver, lampshade, and LED light source. Two groups of aging tests, one test at a normal temperature of 25°C and the other at an elevated temperature of 85°C, are conducted for 2000 h.

It is shown that the decreased output power of the LED driver is 0.015 W on average for the aging test at a normal temperature of 25°C, and it is 0.018 W for the aging test at an elevated temperature of 85°C. The small difference indicates that the elevated temperature of 85°C has little effect on the driver degradation. The degradation of the driver causes a

Table 5. D_1/D_{all}, D_2/D_{all}, and D_3/D_{all} for Six Samples

Aging Temperature (°C)		Driver D_1/D_{all}	Lampshade D_2/D_{all}	LED Light Source D_3/D_{all}	Remaining $1 - (D_1 + D_2 + D_3)/D_{all}$
	No. 1	5.8%	21.7%	69.1%	3.4%
25	No. 2	6.9%	20.3%	69.7%	3.0%
	No. 3	6.7%	21.4%	68.7%	3.2%
	No. 4	3.1%	21.1%	71.8%	4.0%
85	No. 5	2.3%	20.5%	72.4%	4.8%
	No. 6	3.0%	23.0%	71.3%	2.7%

correspondent lumen degradation of 6.5% (at a normal temperature of 25°C) and 2.8% (at an elevated temperature of 85°C) of the total amount on average.

The degradation of the lampshade, coming from the changing of transmittance, causes a correspondent lumen degradation of 21.3% of the total amount on average.

The degradation of the LED light source causes a correspondent lumen degradation of 70.5% of the total amount on average, meaning that the degradation of the LED lamp is mainly attributed to the LED light source.

The elevated temperature of 85°C plays an important role in the degradation of the LED light source and lampshade, with the lumen degradation approximately three times that at a normal temperature of 25°C in this research.

As a starting point, the scope of this study is limited to the LED lamp used in this research. For other kinds of LED lamps with different driver circuits, lamp structures, materials, chips, phosphors, and so on, the worst subsystem should be experimentally determined, but we do believe that the proposed subsystem isolation method can provide a useful way for estimating the reality of LED lamps, especially with current multifarious LED lighting products.

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