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Prediction of Lumen Depreciation and Color Shift for Phosphor-Converted White Light-Emitting Diodes Based on A Spectral Power Distribution Analysis Method

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ABSTRACT The spectral power distribution (SPD) is considered as the figureprint of a light emitting diode (LED). Based on the analysis on its SPD, a method to predict both lumen depreciation and color shift for the phosphor converted white LEDs (pc-LEDs) is proposed in this paper. First, the entire SPD of a pc-LED is predicted by superimposing two asymmetric double sigmoidal (Asym2sig) models, which represent the decomposed blue light and phosphor converted light peaks, respectively. For a better understanding of how the SPD model affects the photometric and colorimetric characteristics of a pc-LED, a sensitivity study of the SPD parameters is then performed on its luminous flux Φ, color coordinates CIE1976(u', v'). Second, the evolutionary process of the SPD is predicted for a pc-LED with the color temperature as 3000 K under degradation testing. And based on these predicted SPDs, the drift curves of Φ, u', v', and $du'v'$ are further predicted. Finally, lifetimes of the pc-LED due to lumen depreciation and color shift are estimated simultaneously from the predicted Φ and $du'v'$ drift curves.

INDEX TERMS Light emitting diodes, spectral analysis, semiconductor device reliability, prediction methods.

I. INTRODUCTION

The lumen depreciation and color shift are two dominant degradation modes of LEDs and LED luminaires. In most of LED reliability studies [1]–[13], they are treated as independent phenomena. In a long period, lumen efficacy is considered as the primary pursuit, resulting in an impression that the luminous flux degradation is the only crucial reliability concern [3]–[10]. In particular, the lifetime of a LED refers to the expected operating hours until light output (e.g. luminous flux) has depreciated to 70% of the initial level, denoted as L70. The Illuminating Engineering Society of North America (IESNA) published a technical memorandum TM-21-11, in which an exponential extrapolation method (herein called TM-21 method) is proposed to estimate the L70 lifetime of LED packages and modules based on LM-80 test data [11], [12]. Later on, a number of studies by Huang *et al.* [2], Fan *et al.* [3], Tseng and Peng [6], van Driel *et al.* [7] etc. were performed on the improvement of the TM-21 method by considering the statistical effects into the L70 lifetime estimation.

Nowadays the LED products are faced with a new era of not only replacing but also exceeding their traditional counterparts (such as incandescent lamps and cold cathode fluorescent lamps). Under this circumstance, the requirements of the color consistence in LEDs become more important than those of lumen maintenance in many applications (such as supermarket, shopping mall, museum, and healthcare lightings). Energy Star, affiliated to the U.S. Environmental Protection

Agency, firstly require that a shift of color coordinates (represented by the Euclidean distance $du'v'$ in the CIE 1976 chromaticity diagram) should not be larger than 0.007 for general lighting applications [14]. In some particular cases, a smaller threshold such as 0.004 or even 0.002 might be adopted for stricter requirements [15]. Nevertheless, the lifetime prediction models for the color shift failure are quite limited. The relevant studies can be referred to the work conducted by Huang *et al.* [2] and Fan *et al.* [16].

As a matter of fact, both the lumen depreciation and color shift of a LED are linked by the degradation of its Spectral Power Distribution (SPD), since the photometric and colorimetric parameters of the LED such as luminous flux, color coordinates, Correlated Color Temperature (CCT), Color Rendering Index (CRI) are originally calculated from its SPD [13], [17]. Many studies related to the improvement of the photometric and colorimetric parameters are performed based on the design and optimization of SPDs. For instance, via the SPD analysis, Lu *et al.* [18] proved that RGB LEDs provide a wider color gamut and smaller color shift than cold-cathode fluorescent lamps, and therefore are more suitable to be used as the backlights of the liquid crystal displays. Lin *et al.* [19] performed a sensitivity study on the CRI parameters (for instance, Ra and R9) of LEDs with different SPDs by using a spectra-loss simulation method. They found that the CRI parameters were significantly sensitive with some certain wavelengths, for instance 444nm, 480nm, 564nm and 622 nm for Ra, whereas 461nm, 581nm and 630nm for R9. As a result, they concluded that extra cautions should be paid on the shift around these wavelengths in the design of SPD for a LED. Song and Han [20] developed an approach to de-convolute the SPD of a phosphor converted white LED (pc-LED) into blue and phosphor converted peaks, each of which was formed by a superposition of several decomposed SPDs in a Gaussian form. Based on these two decomposed peaks, the radiant fluxes of the blue light and phosphor converted light could be calculated for the investigation of the yellow-to-blue ratio and phosphor power conversion efficiency of the pc-LED.

Recently, the SPD analysis has been successfully applied to qualify the reliability of LEDs. Chang *et al.* [21] developed a similarity based metric test method to detect the anomaly point where the color shift failure of the pc-LED is expected to occur. In their method, 24 features including the peak wavelengths, amplitudes, etc. were first extracted from the decomposed blue light and phosphor converted light peaks of the LED. Then a k-nearest neighbor (KNN)-kernel density-based clustering technique was employed to partition the principle components of the 24 features under degradation. Finally, the anomaly was detected when the Euclidean distance from the centroid to the test data for each cluster was beyond the threshold value. Chang's method provides a fast way to detect the failure of the LEDs which could potentially fail during the early stage of operation, however, it is not able to estimate the lifetime of the LEDs.

In order to achieve the goal of lifetime prediction, this paper proposes an SPD analysis based method to predict the time dependency of the photometric and colorimetric parameters of the pc-LED. In this paper, based on the analysis on its SPD, a method to predict both lumen depreciation and color shift of the pc-LED is proposed. The remaining of this paper is organized as follows: Section II discusses the empirical curve-fitting models for describing the SPD of the pc-LED, and a sensitivity study of the model parameters on the photometric and colorimetric parameters. Then Section III demonstrates the prediction of the evolutionary process of the SPDs of the pc-LED under degradation testing, and the estimation of lifetimes of the pc-LED due to lumen depreciation and color shift respectively. In the end, Section IV concludes the paper.

II. SPECTRAL POWER DISTRIBUTION MODELS

As a mixed light, the entire SPD of a white pc-LED is regarded as a superposition of a couple of coincident "bell-shaped" spectra, as shown in (1).

$$SPD_{LED}(\lambda) = \sum_{i=1}^{n} SPD_i(\lambda). \tag{1}$$

in which λ is the wavelength, SPD_{LED} and SPD_i indicate the SPD of the entire LED and i^{th} decomposed component respectively, and n is the total number of the decomposed SPDs. Candidate models for describing the decomposed SPD include the Gaussian function [19]–[23], Asymmetric Gaussian function [24], Asymmetric Double Sigmoidal (Asym2sig) function [25], Lorentzian function [26] etc. Some of them are given in the followings.

1) Gaussian Function

$$SPD = a\exp\left(-\frac{(\lambda-\lambda_c)^2}{w^2}\right). \tag{2}$$

in which parameters a, λ_c and w are the amplitude, peak wavelength, and full width at half maxima (FWHM) respectively.

2) Asymmetric Gaussian Function

$$SPD = \begin{cases} a\exp\left(-\frac{(\lambda-\lambda_c)^2}{w_1^2}\right) & \lambda \le \lambda_c \\ a\exp\left(-\frac{(\lambda-\lambda_c)^2}{w_2^2}\right) & \lambda > \lambda_c \end{cases}. \tag{3}$$

in which parameters a, λ_c, w_1 and w_2 are the amplitude, peak wavelength, left and right FWHMs respectively.

3) Asym2sig Function

$$SPD = a\frac{1-\frac{1}{1+\exp\{-(\lambda-\lambda_c\text{-}w_1/2)/w_3\}}}{1+\exp\{-(\lambda-\lambda_c+w_1/2)/w_2\}}. \tag{4}$$

in which parameters a, λ_c, w_1, w_2 and w_3 are the amplitude, peak wavelength, FWHM, variance of the low-energy and high-energy sides respectively. For decomposed SPDs of a LED, w_1 is always much lower

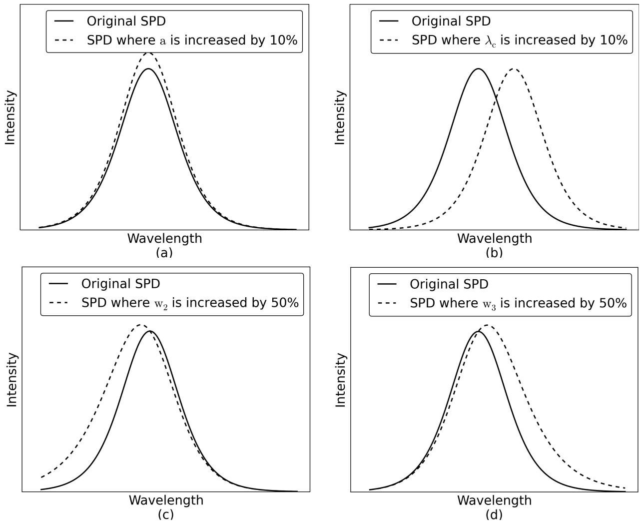

FIGURE 1. Influences of Asym2sig parameters in Eq. (4) on the shape of a decomposed SPD. (a) a; (b) λ_c; (c) w_2; (d) w_3.

than λc, and therefore can be ignored. Then (4) is simplified into (5).

$$SPD = a\frac{1-\frac{1}{1+\exp\{-(\lambda-\lambda_c)/w_3\}}}{1+\exp\{-(\lambda-\lambda_c)/w_2\}}. \quad (5)$$

By using the above-mentioned models to describe a decomposed SPD, the profile of the SPD is related into the change of the model parameters. For instance, Figure 1 shows a comparison between the original and deformed SPDs drawn by (5). The deformed SPDs are created by increasing each of the parameters a, λ_c, w_2, w_3 respectively. Among the four subplots in Fig. 1, it can be seen that:

1) The SPD stretches upward by an increase of 10% of a, as shown in Fig. 1 (a);
2) The whole SPD shifts to the right by an increase of 10% of λ_c, as shown in Fig. 1 (b);
3) The left half of the SPD shifts to the left by an increase of 50% of w_2, as shown in Fig. 1 (c);
4) The right half of the SPD shifts to the right by an increase of 50% of w_3, as shown in Fig. 1 (d);

The number of decomposed SPDs in (1) depends on the fitting accuracy. A superposition of numerous decomposed SPDs can give a high fitting accuracy, but on the other hand tremendously increase the model complexity. From the standpoint of SPD modeling, it is not convenient to investigate the evolution of the SPDs of a LED under degradation by an over-complicated model where each of the parameters influences the SPD deformation in its own way. Thus, in order to reduce the model complexity, the following considerations are implemented.

1) Use the asymmetric model (such as Asymmetric Gaussian Function or Asym2sig Function) in (1), since the decomposed peaks of a LED are usually asymmetric;
2) Reduce the number of decomposed SPDs as less as possible;

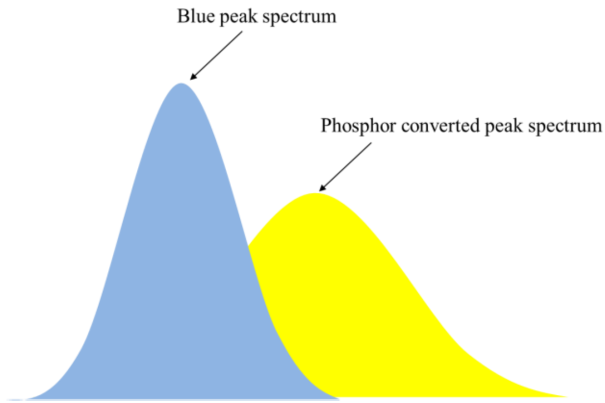

FIGURE 2. Illustration of SPD of a typical pc-LED.

In our study, curve fitting of the SPD of a pc-LED is investigated since the pc-LED occupies a majority market share in white LED lighting applications. As illustrated in Figure 2, the SPD of a typical pc-LED is formed by a superposition of a blue light and phosphor converted light peaks. Therefore the simplest SPD model will be created by superposing two decomposed SPDs indicating the blue light and phosphor converted light peaks respectively. The models to describe the decomposed SPDs can be any one given in (2) to (5), depending on their actual shapes. Eq. (6) shows an expression of the SPD model where the decomposed SPDs are fitted by (5).

$$SPD_{LED}(\lambda) = a_1\frac{1-\frac{1}{1+\exp\{-(\lambda-\lambda_{c1})/w_{31}\}}}{1+\exp\{-(\lambda-\lambda_{c1})/w_{21}\}} + a_2\frac{1-\frac{1}{1+\exp\{-(\lambda-\lambda_{c2})/w_{32}\}}}{1+\exp\{-(\lambda-\lambda_{c2})/w_{22}\}} \quad (6)$$

in which a_1, λ_{c1}, w_{31} and w_{21} are the amplitude, peak wavelength, variance of the low-energy and high-energy sides for the decomposed blue light peak, and a_2, λ_{c2}, w_{32} and w_{22} are for the decomposed phosphor converted light peak. Next, a set of photometric and colorimetric parameters of the LED are calculated by (7) to (10) [14], [15].

(i) Luminous flux Φ

$$\Phi = 683\int_{380}^{780} SPD_{LED}(\lambda)\,V(\lambda)\,d\lambda \quad (7)$$

in which Φ is the luminous flux, $V(\lambda)$ is the spectral luminous efficiency function for photopic vision that describes the visual sensitivity of the human eye in a bright environment, and shown in Fig. 3.

(ii) Chromaticity coordinates (x, y) in CIE1931 color space

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \quad (8)$$

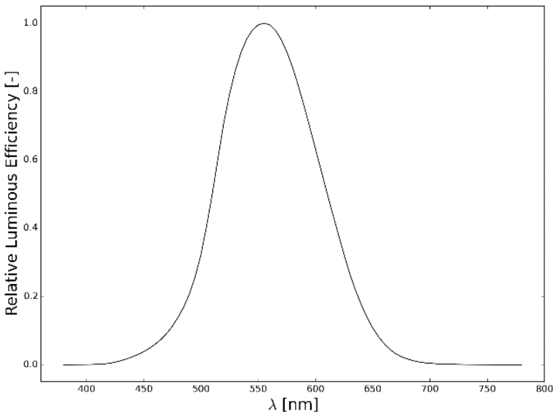

FIGURE 3. Spectral luminous efficiency function for photopic vision. (Reproduced from [14]).

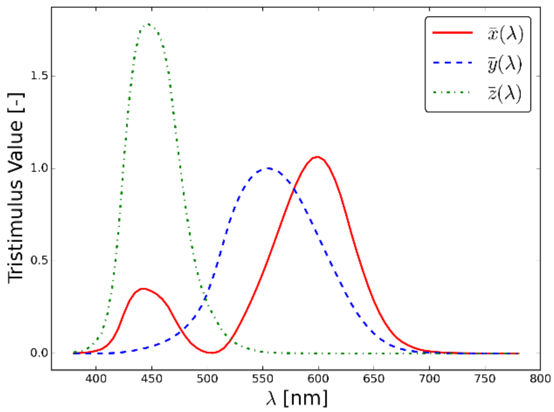

FIGURE 4. Color matching functions. (Reproduced from [15]).

$X = \int_{380}^{780} SPD_{LED}(\lambda)\bar{x}(\lambda)d\lambda$, $Y = \int_{380}^{780} SPD_{LED}(\lambda)\bar{y}(\lambda)d\lambda$, $Z = \int_{380}^{780} SPD_{LED}(\lambda)\bar{z}(\lambda)d\lambda$ in which X, Y and Z are the tristimulus values corresponding to the red, green and blue colors, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the color matching functions shown in Fig. 4.

(iii) Uniform chromaticity scales (u', v') in CIE 1976 color space

$$u' = \frac{4x}{-2x + 12y + 3}, \quad v' = \frac{9y}{-2x + 12y + 3}. \tag{9}$$

(iv) Color shift du′v′

$$du'v' = \sqrt{\left(u' - u'_0\right)^2 + \left(v' - v'_0\right)^2}. \tag{10}$$

in which u'_0 and v'_0 are the initial values of u' and v' respectively.

To investigate the impacts of the SPD parameters on the calculated Φ, u' and v' values, a sensitivity study is performed by the following procedure:

1) Generate an artificial SPD with a set of randomly selected parameters a_1, λ_{c1}, w_{31}, w_{21}, a_2, λ_{c2}, w_{32} and w_{22} of 0.001, 450, 10, 10, 0.001, 600, 50 and 50 respectively. Based on such a SPD, the Φ, u' and v' values are calculated as 14.54, 0.2349 and 0.4741.
2) Increase a single SPD parameter to some extent whereas the others remain the same to observe the changes on the calculated Φ, u' and v' values.

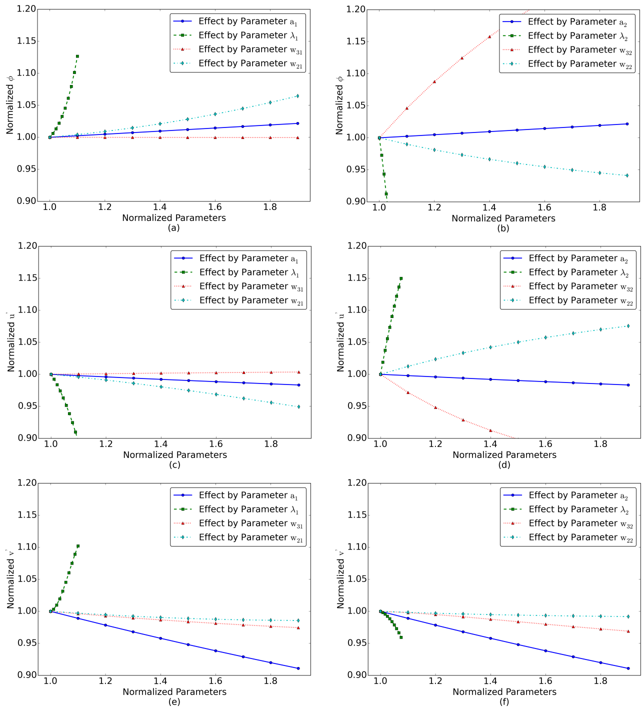

FIGURE 5. Impacts of the SPD parameters in Eq. (6) on the calculated Φ, u' and v'. (a) Impacts of the first 4 SPD parameters on Φ; (b): Impacts of the last 4 SPD parameters on Φ; (c): Impacts of the first 4 SPD parameters on u'; (d): Impacts of the last 4 SPD parameters on u'; (e): Impacts of the first 4 SPD parameters on v'; (f): Impacts of the last 4 SPD parameters on u'.

Fig. 5 shows the results of the sensitivity study. For comparison purpose, all eight SPD parameters as well as the calculated Φ, u' and v' values are normalized by their initial values. From all subplots in Figure 5, the parameters λ_{c1} and λ_{c2} are found the most sensitive to the calculated Φ, u' and v' values. This is because they determine the peak wavelengths of the blue light and phosphor converted light peaks respectively. As shown in Figure 1 (b), a small change of the λ_c parameter yields a significant shift of the SPD, resulting in a great change on the photometric and colorimetric parameters as well. On the contrary, the parameters a_1 and w_{31} hardly affect the Φ and u' calculations, since the difference on the decomposed blue light SPDs caused by these two parameters, as shown in Figure 1 (a) and (c), do not significantly contribute the calculation of the Φ and u' values. For the similar reason, the parameters w_{31}, w_{21}, w_{32} and w_{22} also weakly affect the v' calculation, whereas the parameter a_1 weakly affects the u' calculation. To conclude, the impacts of the SPD parameters on the Φ, u' and v' calculations are summarized in Table 1, in which "H", "S" and "L" indicate "highly sensitive", "sensitive" and "less sensitive" respectively.

TABLE 1. Summary of the sensitivity study results of the SPD parameters.

	Φ	u'	v'
a_1	L	L	S
λ_{c1}	H	H	H
w_{31}	L	L	L
w_{21}	S	S	L
a_2	S	L	S
λ_{c2}	H	H	H
w_{32}	S	S	L
w_{22}	S	S	L

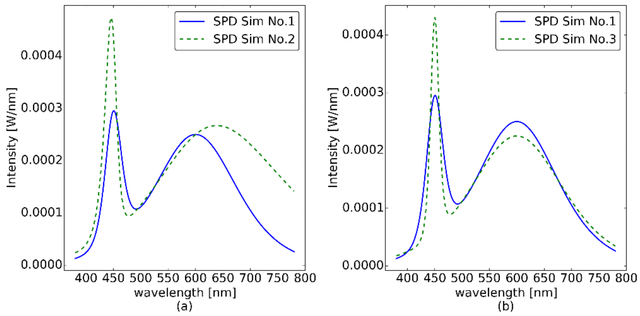

FIGURE 6. Illustration of two special pairs of SPDs. (a): resulting in same Φ but different u' and v'; (b): resulting in same u' and v' but different Φ.

TABLE 2. Parameters of the SPDs shown in Fig. 6 and the calculated Φ, u' and v' values.

ID	a_1	λ_{c1} (nm)	w_{31}	w_{21}
Sim No.1	0.001	450	10	10
Sim No.2	0.0015	450	10	5
Sim No.3	0.0015	450	5	5
ID	a_2	λ_{c2} (nm)	w_{32}	w_{22}
Sim No.1	0.001	600	50	50
Sim No.2	0.001	600	60	103
Sim No.3	0.0009	600	56.5	56.5
ID	Φ (lm)	u'	v'	
Sim No.1	14.54	0.2349	0.4741	
Sim No.2	14.54	0.2441	0.4544	
Sim No.3	13.56	0.2349	0.4741	

According to the above-mentioned discussions, it is possible to theoretically find a pair of SPDs giving the same Φ but different u' and v', and vice versa. Examples of these two circumstances are illustrated by the SPDs Sim No.1 and No.2 in Figure 6 (a) and Sim No.1 and No.3 in Figure 6 (b) respectively. Exact values of the SPD parameters and the calculated Φ, u' and v' values of the SPDs Sim No.1 to No.3 are given in Table 2.

III. DEGRADATION PREDICTION

For verifying the proposed method, the entire SPD of a 3000K pc-LED under a driving current of 180mA was fitted by using (6). The goodness-of-fit was examined by the

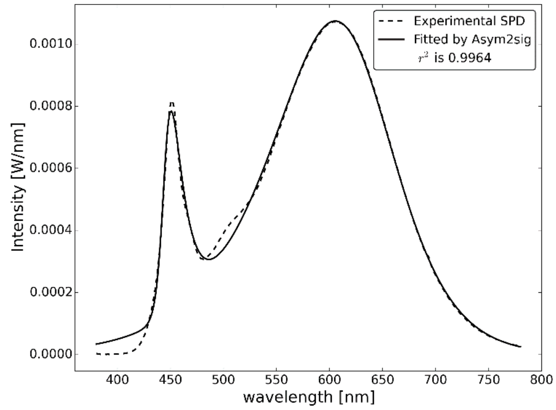

FIGURE 7. Experimental and fitted SPDs of a 3000K pc-LED test at initial time.

TABLE 3. Measurements and predictions of the initial photometric and colorimetric parameters.

	Measurement	Prediction
Φ (lm)	55.05	55.02
u'	0.2498	0.2506
v'	0.5082	0.5078

coefficient of determination r^2 calculated by (11).

$$r^2 = 1 - \frac{\sum_{i=1}^{n} \left(y_i - y_{i,pred}\right)^2}{\sum_{i=1}^{n} \left(y_i - y_{avg}\right)^2}. \tag{11}$$

in which y_i and $y_{i,\text{pred}}$ are the i^{th} value of the SPD and its fitting estimation, y_{avg} is the average of all values on the SPD. As shown in Fig. 7, a good agreement between the experimental and fitted SPDs is obtained through a high r^2, except for the left tail less than 430 nm caused by a broad width of the decomposed phosphor converted peak. This fitting error has no effect on the prediction of Φ since the $V(\lambda)$ function less than 430 nm is nearly zero. However, it might give an overestimated X and Z tristimulus values to cause a high prediction on u', but a lower prediction on v' .

From both experimental and fitted SPDs, measurements and predictions of the Φ, u' and v' values of the pc-LED were calculated and compared in Table 3. It can be seen that a good agreement can be achieved in between the measured and predicted values. That means the influence of the fitting error at the left tail can be neglected in this case.

Then the test for the 3000K pc-LED continued at a solder temperature of 105° for 4600 hours, in which the SPD was measured after about every 200 hours. As shown in Fig. 8, the SPD of the pc-white LED gradually degrades with the increase of the operational time from 0 hour to 4600 hours. When using (6) to fit all of the degraded SPDs, the increase or decrease models of the eight parameters were fitted by two candidate models expressed by (12) and (13)

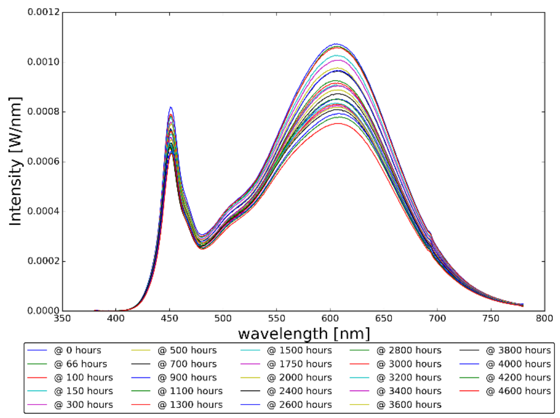

FIGURE 8. Evolutionary SPDs of the test sample under degradation.

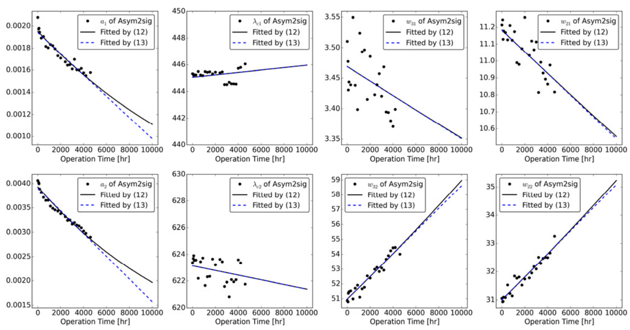

FIGURE 9. Evolution of the eight SPD parameters extracted from the SPDs of the pc-LED under degradation and their fitting curves by using (12) and (13).

respectively.

$$par = C_1 \exp(C_0 t). \quad (12)$$

$$par = C_0 t + C_1. \quad (13)$$

Both (12) and (13) are empirical models in which *par* denotes one of the SPD parameters, t is the ageing time, C_0 and C_1 are the fitting parameters estimated by the Maximum Likelihood Estimation (MLE) method. Fig. 9 shows the extracted values of all of the SPD parameters from the degraded SPDs and the corresponding exponential fitting curves. It can be seen that (12) and (13) provide very similar fitting curves to variation of the SPD parameters except for a_1 and a_2 where the deviation in between the two fitting curves is gradually increased as the operational time rises. Compared to (12), (13) gives an overestimated degrading curve that will probably cause significant error in predicting pc-LED's photometric and colorimetric parameters. Therefore, (12) is finally adopted in our work to predict the time dependent evolution of all SPD parameters of the pc-LED.

In addition, it is interesting to note that the changing trends are observed oppositely in between the parameters λ_{c1}, w_{32}, w_{22} belong to the blue peak spectrum and the parameters λ_{c1}, w_{32}, w_{22} belong to the phosphor converted peak spectrum. This reveals the difference in between the electroluminescence ageing mechanism that exists in the blue chip and the photoluminescence ageing mechanism that exists in the phosphor/silicone composite materials.

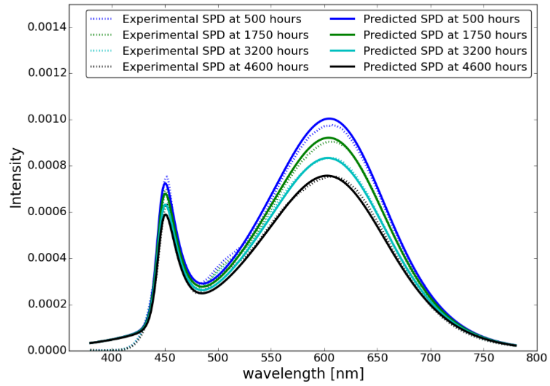

FIGURE 10. Experimental and predicted SPDs of the pc-LED aged until 500 hours, 1750hours, 3200 hours and 4600 hours.

TABLE 4. Extracted fitting parameters of (12) for the 8 SPD parameters.

	a_1	λ_{c1} (nm)	w_{31}	w_{21}
C_0	-5.65E-5	2.04E-7	-3.44E-6	-5.79E-6
C_1	1.95E-3	4.45E2	3.47E0	1.12E1
	a_2	λ_{c2} (nm)	w_{32}	w_{22}
C_0	-6.93E-5	-2.83E-7	1.46E-5	1.28E-5
C_1	3.93E-3	6.23E2	5.10E1	3.10E1

TABLE 5. R^2 Parameters of the SPD predictions at different operational times.

	500 hours	1750 hours	3200 hours	4600hours
r^2	0.9947	0.9950	0.9938	0.9930

The extracted values of C_0 and C_1 of (12) in relevance to each of the SPD parameters of the 3000K pc-LED are given in Table 4. After the C_0 and C_1 values for each of the SPD parameters were determined, the evolutionary process of the SPDs of the pc-LED was predicted. Figure 10 displays the predicted SPDs at a few operational time points compared with the experimental curves, and the r^2 parameters calculated by (11) from the experimental and predicted SPDs are given in Table 5. Reasonable agreements can be observed in between these experimental and predicted SPDs, except for a bias at the left tail (less than roughly 430 nm).

Based on the predicted evolutionary process of the SPDs, the degradation curves of Φ, u', and v' of the pc-LED were predicted by using (7) to (9). Comparisons in between these predicted curves and the experimental measurements are shown in Fig. 11 (a), (b) and (c) respectively. The predicted Φ and v' curves match the experimental measurements very well. Nevertheless, the predicted u' curve stays a little higher than the experimental measurements. This is mainly because of the matching error at the left tail of the SPDs as mentioned in the preceding section. In addition, by using (10),

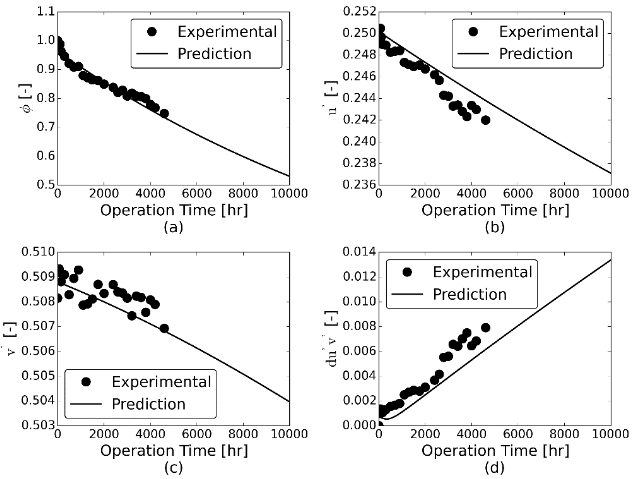

FIGURE 11. Experimental measurements and predicted curves of (a): Φ; (b): u'; (c): v' and (d): $du'\ v'$ of the pc-LED.

the degradation curve of $du'\ v'$ was further predicted and shown in Fig. 11 (d) in comparison with the experimental measurements. Finally, according to the predicted degradation curves of Φ and $du'\ v'$, the L70 lifetime (where the lumen maintenance decays to 0.7) is estimated as 5402 hours, whereas the color maintenance lifetime (where $du'v'$ grows to 0.007) as 5214 hours.

IV. CONCLUDING REMARKS

In this paper, a SPD analysis based method is proposed to simultaneously predict the lumen depreciation and color shift of pc-LEDs. In this method, the entire SPD of the pc-LED was firstly predicted by a superposition of two Asym2sig Functions, which were used to describe the blue light and phosphor converted light peaks respectively. And then impacts of the SPD parameters on the calculated Φ, u' and v' values of the pc-LED were discussed in a sensitivity study. During the process of ageing of the pc-LED, the SPD was observed to gradually degrade in such a way that the SPD parameters increased or decreased in an exponential form. After obtaining the pair of fitting parameters to describe the growing/decaying trend of each of the SPD parameters, an evolutionary process of the SPDs of the pc-LED under degradation was predicted, and then the drift curves of Φ, u' and v' were predicted. Based on the experimental and prediction results on a 3000K pc-LED, the proposed method gives reasonable predictions on the degradation curves of Φ, u' , v' and $du'\ v'$. Lastly, from the predicted drift curves of Φ and $du'\ v'$, the L70 and color maintenance lifetimes of the pc-LED were estimated as 5402 hours and 5214 hours respectively.

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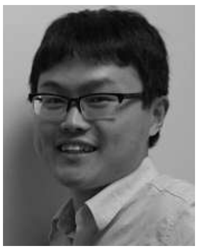

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