Journal of Information Display
Vol. 13, No. 1, March 2012, 37–42

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Analysis of the spectral characteristics of white light-emitting diodes under various thermal environments

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(*Received 7 October 2011; Revised 2 December 2011; Accepted for publication 5 December 2011*)

An empirical functional form was suggested for the analysis of the emission spectrum of high-power light-emitting diode (LED) consisting of a sharp blue peak from the LED chips and a broad yellow peak from the phosphor layer. The peak positions, half widths, shape parameters, and amplitudes of these two peaks were reliably obtained as a function of the temperature, and the results were discussed qualitatively in relation with the junction temperature. The adoption of an inert liquid was found to have significantly reduced the LED temperature and the color shift of the emitted light. The phenomenological approach used in this study may be helpful in the simulation of the LED spectrum under various thermal conditions, and may thus be helpful in the improvement of the device performance.

Keywords: LED; spectrum; peak fitting; inert liquid; junction temperature

1. Introduction

The application of the light-emitting diode (LED) light source has been accelerating in various fields, including general lighting and backlights for liquid crystal displays [1–2]. LED has many advantages over the traditional light sources, such as incandescent and fluorescent lamps, including the fact that it is highly efficient, has a compact design, and is digitally controlled. A combination of tri-color LEDs with sharp emission peaks is highly desirable for achieving a wide color gamut for display applications, while phosphor-based white LEDs with broad spectral features are suitable for general lighting where a color-rendering index is important. These white LEDs are usually designed based on the combination of short-wavelength excitation light and the Stokes-shifted phosphor emissions [3].

The emission spectrum from LED is affected by many factors, including the driving conditions (current and voltage) and ambient temperature, which in turn determine the junction temperature of the LED chips. These factors have a direct effect on the density of states and carrier concentrations in the semiconductor, and thus change the emission spectrum. The changes in the spectrum result in a corresponding change in the color gamut of displays or in the color-rendering index of LED lighting. In particular, the effect of temperature on LED may be one of its most serious aspects because the junction temperature of LED easily rises to temperatures much higher than 100°C. The thermal characteristics of high-power LED, and their control, are extremely important in improving the device efficiency and its long-term reliability. The expected lifetime of LED will decrease with the operating temperature. One approach to solving this thermal problem may be to use an inert liquid in the LED lighting package to maintain a low-temperature environment for LED operation.

As the changes in the electrooptic properties of LEDs are currently important technical issues from the viewpoint of application, it is necessary to reflect these changes in the design of LED-based devices to maintain and optimize the device performance. If the spectral characteristics can be accurately predicted as functions of the driving current and temperature, these data can be utilized to calculate the device performance under sudden changes in the ambient conditions, and to optimize the feedback signal to the LED devices. To do this, the exact spectral features should be analyzed and modeled by means of appropriate spectral functions. Several models have been proposed in previous studies for this modeling, including a Gaussian model, a double Gaussian model, a split Gaussian model, and other more complex forms [4,5]. These previous studies, however, were limited to the phenomenological modeling of the emission spectrum from LED chips, and to these authors' knowledge, there has been no effort to analyze and model the whole spectrum, including the phosphor emission peaks.

The current study aimed to investigate the white spectrum consisting of sharp blue emission and broad yellow-phosphor emission to construct a phenomenological model for interpretation, and to determine the effect of inert liquid paraffin on the thermal and spectral characteristics

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ISSN 1598-0316 print/ISSN 2158-1606 online
© 2012 The Korean Information Display Society
http://dx.doi.org/10.1080/15980316.2012.652254
http://www.tandfonline.com

of high-power white LEDs. The dependence of the peak wavelength, half width, and skewness of each spectrum on various thermal conditions was analyzed based on empirical functions.

2. Experiment

A 10-W high-power LED manufactured by GLS Co., was used for the experiment, which is shown in Figure 1(a). The emission area of this LED was 12.8 × 8.3 mm^2. The total number of blue LED chips included in one package was 48, which were arranged by 8 × 6 on the emission area, and these chips were covered with a yellow-phosphor material. The white LED was driven by a DC voltage of 23 V and a current of 0.44 A, which means that the total power consumption was 10.1 W. The driving current was fixed under temperature change. The spectrum in the visible range, the luminance, and the color coordinates were measured using a spectroradiometer (PR670, Photo Research Co.). The acquisition time for the measurement of one spectrum was only 10 ms, and the temperature variation during this short time was negligible. Figure 1(b) shows the normalized emission spectrum of the white LED measured at room temperature, which consisted of a blue peak located at about 450 nm emitted from the LED chips, and a broad yellow peak at ∼560 nm emitted from the phosphor particles. The color coordinates were $x = 0.35$, $y = 0.38$ (correlated color temperature = 4914 K).

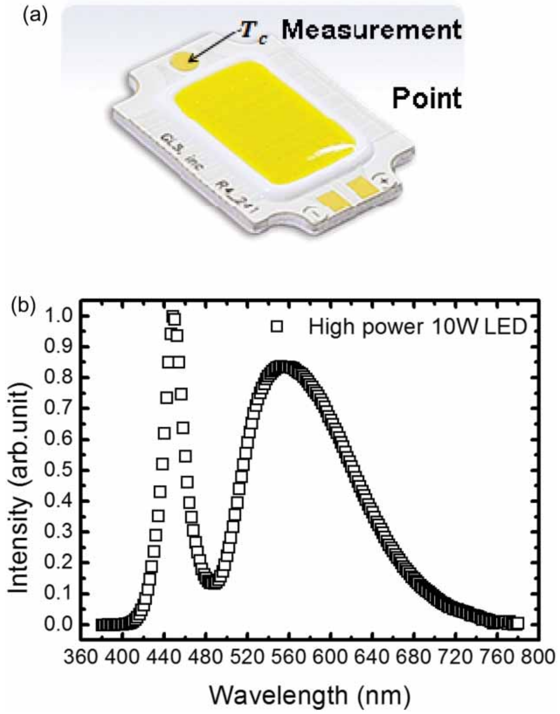

Figure 1. (a) Photograph of the 10-W white LED (GLS Co.) used in this study and (b) a normalized emission spectrum of this white LED.

Table 1. Density and kinematic viscosity of paraffin oil purchased from Kukdong Oil & Chemicals Co.

Paraffin Oil	Specific Gravity (15/4°C)	Kinematic Viscosity at 37.8°C (cSt)
LP 50F	0.826	50
LP 75F	0.832	75
LP 100F	0.837	100
LP 150F	0.840	150

Inert insulating liquid can be adopted in the package of LED-illuminating devices to reduce the thermal problems caused by the heat generated from LED. In the current study, liquid paraffin was used for this purpose because it is transparent, inert, non-volatile, and insulating. Four types of liquid paraffin (LP50F, LP75F, LP100F, and LP150F) were purchased from Kukdong Oil & Chemicals Co. The specific heat of this oil is 0.7 kcal/kg. Paraffin oil is classified according to the kinematic viscosity, defined by the viscosity divided by the density, measured at 37.8°C. The specific gravity and the kinematic viscosity at 37.8°C of all the paraffin oils are shown in Table 1. The inset of Figure 2 shows a photograph of the paraffin oil that was used in this study. The high-power LED that was set up on a heat-release board was inserted in a beaker, and then the liquid paraffin was poured into the beaker in the following amounts: 100, 200, and 300 ml. At the amount of 100 ml, only the heat-release board sank in the oil; the total LED package sank in the oil at the amounts of 200 and 300 ml. Multi-channel thermocouples were used for temperature measurement. The temperature and emission spectrum of LED were recorded at 1-min intervals, starting from the time that the LED was turned on.

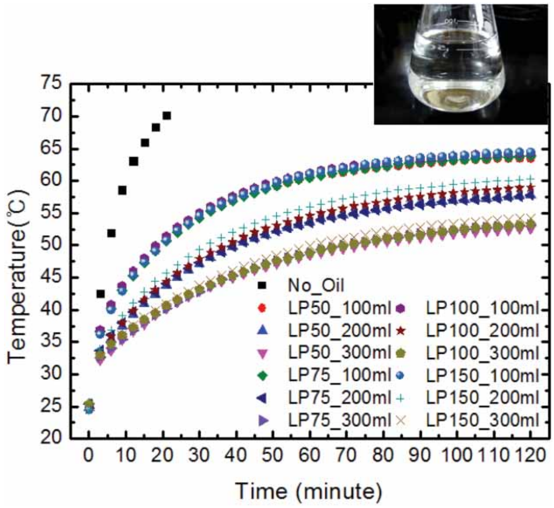

Figure 2. Time dependence of the temperature measured at the 'measurement point' shown in Figure 1(a) under each condition. The inset shows a photograph of the paraffin oil used in this study.

3. Results and discussion

Figure 2 shows the change in temperature, which was recorded at the ‘measurement point’ shown in Figure 1(a), as a function of time under each condition. As expected, the temperature change became smaller as the amount of paraffin increased, because of the high thermal conductivity of the liquid, and the convection effect. The time dependence of temperature could be fitted using a single exponential function, and the time constant increased with the liquid amount [6], indicating that the adoption of an inert liquid is an effective way to release the heat generated from blue LED chips. The time constant was not dependent on the kinematic viscosity of the paraffin oil in the examined range [6].

Figure 3(a) and (b) shows the typical emission spectra of white LEDs under two different amounts of oil and at two different temperatures, respectively, along with the best-fitted lines, as described below. Figure 3(a) suggests that the height of the yellow peak emitted from the phosphor layer decreased substantially when the LED was immersed in the paraffin oil, which can in part be attributed to the transmission characteristic of the oil in the visible range, and in part to the effect of the temperature on the phosphor emission. This resulted in the blue shift of the color coordinates and the generation of a cool white light. For the quantitative analysis of the change in the spectral characteristics of high-power LED, it would be very useful to find out the appropriate functions by which the peak position, amplitude, and asymmetry could be obtained [4,5]. To find the exact empirical functions that would fit the measured spectrum, various available spectroscopic functions, including all the functions introduced by Reifegerste and Lienig [4], were used to fit the measured spectrum under different conditions, using commercial software programs. The least-square R^2 coefficient was monitored to check the reliability of the fitting process and to determine the most appropriate functional form to model the spectrum. Based on trial-and-error analysis, it was found that the Gaussian–Lorentzian cross-product function (GLCPF; Equation (1)) was the most appropriate for the blue peak located at ∼450 nm, and that the asymmetric double sigmoidal function (ADSF; Equation (2)) was the best fit for the broad yellow peak.

$$y = y_0 + \frac{A}{1 + (e^{0.5(1-s)(x-x_c)^2/w^2} s(x-x_c)^2/w^2)}, \tag{1}$$

$$y = y_0 + A\frac{1}{1+e^{-(x-x_c+w/2)/S_1}}\left(1 - \frac{1}{1+e^{-(x-x_c+w/2)/S_2}}\right). \tag{2}$$

In the above equations, x is the wavelength in the unit of nm; y the intensity at x; A the amplitude parameter; x_c the center wavelength; w the width; and s, s_1, and s_2 the skew parameters (or shape parameters). The baseline y_0 was found to be zero. The solid lines in Figures 3 and 4 show the best-fitted result for the measured spectrum by combining Equations (1) and (2). Figure 4 clearly shows that the LED spectrum can be fitted satisfactorily using the superposition of the above two functions. The R^2 coefficient was >0.99 for all the cases. It should be pointed out, however, that the above empirical equations have no physical meaning and are considered useful mathematical tools for fitting the measured spectrum of white LED.

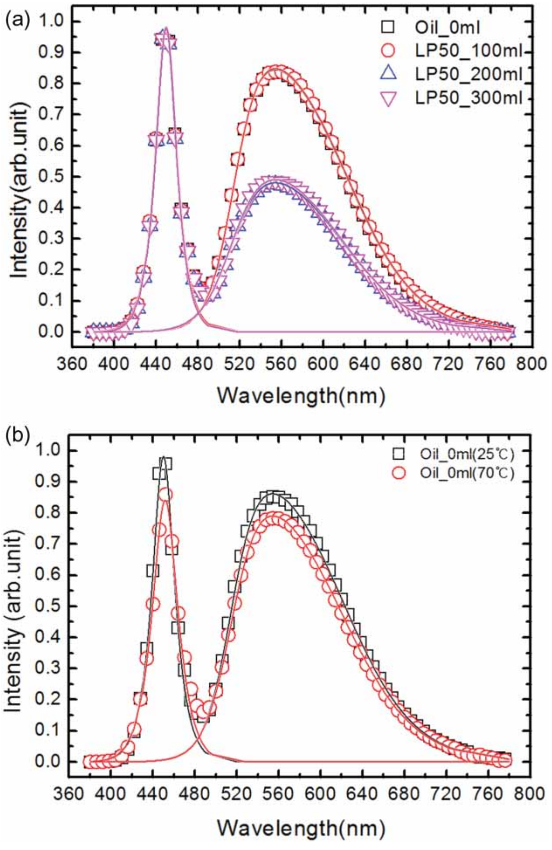

Figure 3. The emission spectrum of the white LED (a) with different amounts of oil, at room temperature, and (b) at two different temperatures, without any oil.

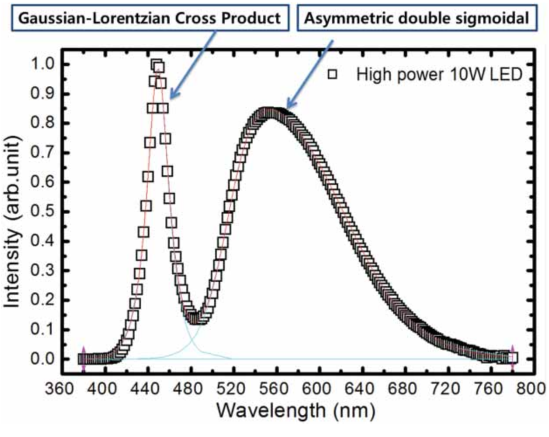

Figure 4. The measured spectrum (solid squares) of the white LED at room temperature, and the best-fitted result (solid lines: red for combined, cyan for individual peak), using Equations (1) and (2).

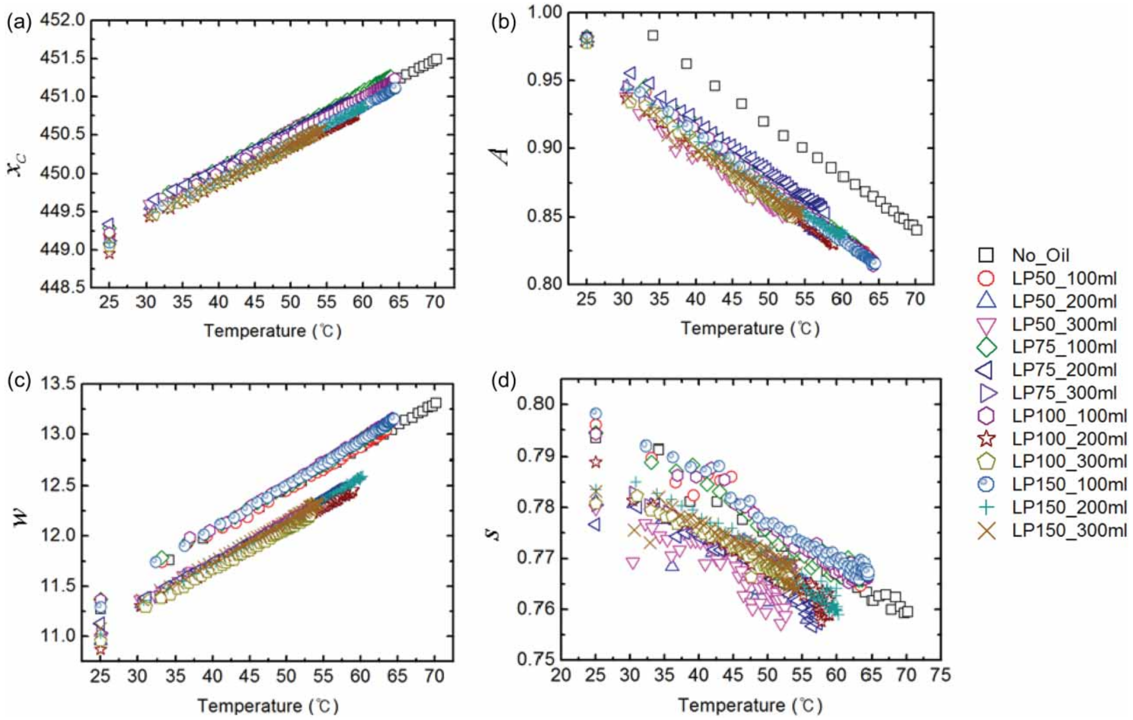

Figure 5. The dependence of the four fitting parameters of GLCPF used for fitting the blue emission peak onto the temperature: (a) peak position; (b) amplitude; (c) half width; and (d) skewness.

Figure 5 summarizes the dependence of the four fitting parameters of GLCPF used for fitting the blue emission peak onto the temperature. Basically, the measured temperature is expected to be proportional to the junction temperature. The peak wavelength increases with the temperature, indicating a downward frequency shift. This change can be associated with the change in the energy gap of the semiconductor with the temperature. According to the Varshni formula, the bandgap energy decreases linearly upon heating above room temperature [7]. This linear change in the energy bandgap is reflected in the monotonous change in the wavelength with the temperature. The half width and the skewness shown in Figure 5(c) and (d), respectively, are related to the carrier temperature and are expected to exhibit a linear change because the carrier temperature variation is also linear with the junction temperature [5]. The decrease in the amplitude shown in Figure 5(b) suggests that the radiant power decreases with the temperature, which can be attributed to the increase in the probability of nonradiative recombination at a higher junction temperature. The splitting of curves shown in Figure 5 mainly depends on whether the LED is covered by the inert liquid or not. This indicates that the spectral changes due to the inert liquid affect the width and the shape parameter of the blue emission peak.

Figure 6 shows the temperature dependence of the five parameters of ADSF used for fitting the broad phosphor spectrum. In spite of the fact that all the five parameters displayed linear behaviors, their changes were very mild compared to those of the blue emission peak in the investigated temperature range, as compared to Figure 5. This shows that the effect of the temperature on the phosphor emission is less substantial than that on the blue LED chip. As ADSF has two skew parameters, however, a direct interpretation of these in relation with the physical properties is not easy. The two data groups shown in Figure 6(a), (b), and (d) indicate that the spectral characteristics exhibit substantial changes depending on whether the LED is covered by paraffin oil (conditions of 200 and 300 ml) or not (conditions of 0 and 100 ml). That is, the splitting of curves in Figure 6 suggests that the spectral changes induced by the inert liquid mainly affected the center wavelength, amplitude, and shape parameter s_1. The temperature dependence of all the parameters shown in Figures 5 and 6 can be fitted using the simple linear relation $a + bT$, where a and b are the fitting parameters and T is the temperature. The numerical values of these fitting parameters are shown in Tables 2 and 3. All the linear behaviors of the fitting parameters shown in Figures 5 and 6 enable the simulation of the emission spectrum of white LED, and the calculation of the lighting performance at a certain temperature range that is large enough for practical applications. This information can be used, for example, in the feedback system of the LED lighting system, to maintain the device performance.

Finally, it should be noted that the meaningful interpretation of the parameter values obtained in the current study based on semiconductor physics is important for the

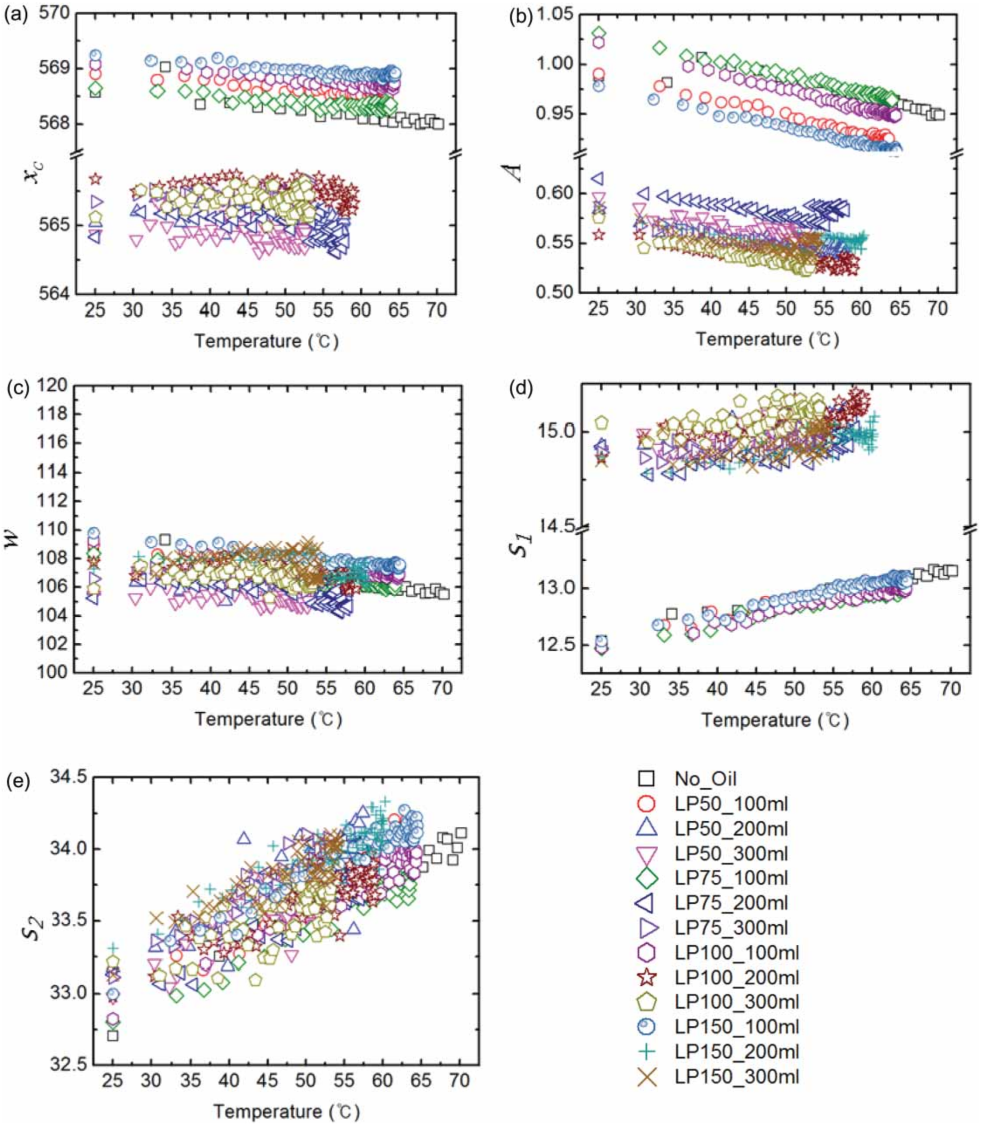

Figure 6. Dependence of the five fitting parameters of ADSF used for fitting the yellow emission peak onto the temperature: (a) peak position; (b) amplitude; (c) half width; and (d,e) skewness parameters.

Table 2. Numerical values of the parameters *a* and *b* of the linear relation $a + bT$, which were used to fit the data shown in Figure 5.

	x_c (nm)		*A* (Arb. unit)		*w* (nm)		*s*	
	a (nm)	*b* (nm/°C)	*a*	*b*	*a* (nm)	*b* (nm/°C)	*a*	*b* (1/°C)
No Oil	448.0	0.0490	1.092	−0.0035	10.26	0.0436	0.8138	−0.000778
LP50 100 ml	448.0	0.0499	1.078	−0.0041	10.26	0.0439	0.8153	−0.000765
LP50 200 ml	448.0	0.0489	1.074	−0.0041	10.02	0.0419	0.8011	−0.000703
LP50 300 ml	448.0	0.0502	1.056	−0.0039	10.06	0.0415	0.7975	−0.000669
LP75 100 ml	448.1	0.0501	1.086	−0.0042	10.03	0.0441	0.8141	−0.000755
LP75 200 ml	448.1	0.048	1.072	−0.0038	10.08	0.0415	0.8047	−0.000766
LP75 300 ml	448.0	0.0482	1.066	−0.0039	10.05	0.0412	0.7998	−0.000608
LP100 100 ml	448.0	0.0502	1.076	−0.0040	10.28	0.0445	0.8158	−0.000777
LP100 200 ml	447.9	0.0490	1.059	−0.0039	9.951	0.0425	0.8070	−0.000785
LP100 300 ml	448.0	0.0479	1.067	−0.0041	9.996	0.0415	0.8022	−0.000672
LP150 100 ml	448.0	0.0489	1.072	−0.0040	10.25	0.0449	0.8186	−0.000808
LP150 200 ml	448.0	0.0484	1.055	−0.0037	9.988	0.0432	0.8017	−0.000843
LP150 300 ml	448.0	0.0469	1.048	−0.0036	10.08	0.0413	0.8011	−0.000632

Table 3. Numerical values of the parameters a and b of the linear relation $a + bT$, which were used to fit the data shown in Figure 6.

	x_c (nm/°C)		A (Arb. unit)		w (nm)		S_1		S_2	
	a (nm)	b (nm/°C)	a	b	a (nm)	b (nm/°C)	a	b (1/°C)	a	b (1/°C)
No Oil	569.1	−0.0163	1.038	−0.0011	110.5	−0.0713	12.29	0.0126	32.26	0.0259
LP50 100 ml	569.2	−0.0101	1.036	−0.0018	110.4	−0.0627	12.21	0.0136	32.21	0.0281
LP50 200 ml	565.6	−0.0109	0.598	−0.0010	108. 2	−0.0451	14.73	0.0058	32.61	0.0236
LP50 300 ml	565.1	−0.0059	0.608	−0.0010	106.5	−0.0220	14.74	0.0056	32.70	0.0183
LP75 100 ml	568.8	−0.0079	1.074	−0.0017	109.7	−0.0573	12.17	0.0131	32.13	0.0272
LP75 200 ml	565.6	−0.0128	0.614	−0.0006	108.4	−0.0533	14.57	0.0076	32.37	0.0260
LP75 300 ml	565.3	−0.0035	0.613	−0.0014	106.4	−0.0166	14.71	0.0057	32.59	0.0245
LP100 100 ml	569.3	−0.0094	1.067	−0.0019	110.6	−0.0583	12.15	0.0137	32.22	0.0275
LP100 200 ml	566.0	−0.0102	0.573	−0.0008	109.0	−0.0384	14.77	0.0062	32.50	0.0229
LP100 300 ml	565.4	−0.0014	0.592	−0.0012	107.1	−0.0036	14.84	0.0049	32.60	0.0202
LP150 100 ml	569.4	−0.0088	1.019	−0.0016	111.0	−0.0555	12.24	0.0133	32.47	0.0267
LP150 200 ml	566.4	−0.0133	0.581	−0.0005	110.2	−0.0532	14.59	0.0067	32.76	0.0229
LP150 300 ml	566.1	−0.0048	0.589	−0.0008	108.9	−0.0212	14.73	0.0043	32.73	0.0229

improvement of the modeling. It would be very desirable to express the fitting parameters in Figures 5 and 6 in terms of important physical properties, such as the junction temperature, driving current, and bandgap energy, which has yet to be studied in the near future.

4. Summary

The changes in the spectral characteristics of high-power LED were studied under various thermal conditions. Two empirical functions were suggested for the sharp blue peak and the broad phosphor emission peak from the phenomenological point of view, by which the measured LED spectrum could be fitted reliably. The temperature dependence of the peak positions, amplitudes, half widths, and degree of asymmetry (shape parameters) could be obtained for both emission peaks. These data can be used to simulate the emission spectrum under various temperature conditions, and thus, to estimate and maintain the device performance. The current study showed that the adoption of an inert liquid such as paraffin oil may be an effective way of reducing the thermal problems in LED devices, and to minimize the changes in the emission spectra resulting in the reduced color drift of such devices. The addition of paraffin oil, however, resulted in the blue shift of the emitting light from the high-power LED, which should be considered in practical application.

Acknowledgement

This research was supported by the Korea Sanhak Foundation.

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