Precision Lighting of LED Array using an Individually Adjustable Color Temperature and Luminous Flux Technology

Min-Wei Hung, Wen-Ning Chuang, Cheng-Ru Li, Kuo-Cheng Huang and Yu-Hsuan Lin
Instrument Technology Research Center, National Applied Research Laboratories, Hsinchu, Taiwan

Keywords: White Light Led, Color Temperature, Pulse Width Modulation.

Abstract: This paper presents a novel white light LED array equipped with a 3-pulse-width-modulation (PWM) control module that could separately adjust either the color temperature or luminous flux without influence on the other. An optical measurement system was set up to provide the complete information of color temperature, illuminance and spectrum of the LED array for analysis. The radiometry quantity of spectral data was converted into photometry quantity. The average percent deviations of color temperatures with a fixed illuminance, and illuminances with a fixed color temperature were estimated, respectively. Comparing with the existing commercial products, the developed LED array has better adjustability, stability and precision. The proposed innovations represent a novel solution for white light LED lighting technology and related applications.

1 INTRODUCTION

Light emitting diode (LED) is a kind of semiconductor light source, which emits light when a driving voltage is applied. The optical properties of LED light are monochromatic, non-coherent, non-polarized and divergent (Nadarajah and Yimin, 2005; Ye, et al., 2010). In recent years, LED industry becomes increasingly popular because of energy lack and carbon emission problems. Due to the advantage of long lifetime, low power consumption, good luminous efficiency, faster switching and small size of LED, it has been regarded within the scope of green lighting. Nowadays, LED has been widely used in light bulb, car headlight, photography lights, billboards and versatile environmental lighting applications. In order to increase the brightness of LED lighting for practical usage, the LED chips are usually arranged as an array device. In the field of photography, white light LEDS are often used in supplementary light of portrait photography. Conventional bulb-type lamps might be replaced because of LED light's lightweight and portability characteristics. Color temperature is a characteristic of white light, which could be described by the temperature of an ideal blackbody radiator that radiates light. Traditionally, the color temperature of LED photography lights is variable by simply changing the color filters. However, the filter types are limited and spectral discontinuous. Because the kinds of ambient light are various and the human eye is very sensitive to the wavelength and brightness of lights, white balance in continuous regime is hard to be achieved by using the color filters.

To overcome the problem described above, a LED light source that can spectral-continuously compensate the white balance should be developed. However, multiple pieces of the same white light LED chips assembled in a lamp can only increase the total brightness of light, but cannot change the original spectral characteristics. Fortunately, the commercial white light LED product is composed of the blue light LED and yellow phosphor. According to the demand of application, the phosphor ratio in LED is adjustable. It means that the white light LED products with various color temperature are individually manufacturable (Ingo and Marc, 2006, (Sheu, et al., 2003, Yoshi, 2005, Guoxing and Huafeng, 2011, Guoxing and Lihong, 2010, Jung-Chieh and Chun-Lin, 2009, Elodie, et al., 2009). Typical white light LED products have several types of color temperature: 2700K、3000K、3500K、4000K、4500K、5000K、5700K、6500K. Color temperatures over 5000 K are called cool white, and color temperatures lower than 3000K are called warm white. With these color temperatures, the optical lighting with spectral-continuous color temperature could be achieved by mixing the various

Hung M., Chuang W., Li C., Huang K. and Lin Y.
Precision Lighting of LED Array using an Individually Adjustable Color Temperature and Luminous Flux Technology.
DOI: 10.5220/0006112001830190
In *Proceedings of the 5th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2017)*, pages 183-190
ISBN: 978-989-758-223-3

LEDs. The contribution of each kinds of LED could be individually controlled by their own driver circuit. Actually, some of the products developed by the above-mentioned method have been successfully applied to the household lighting. However, the stability and precision of the color temperature and brightness are not good. Although these products can be effectively applied to the field of photography and home lighting, they cannot be applied to the field of spectral optics.

In this paper, a white light LED array that can be separately adjusted color temperature and luminous flux was developed. The device is composed of two kinds of LED chips and a corresponding driving circuit. The color temperatures of two kinds of LED chips are 2800K and 4900K, respectively. The driving circuit using 3-PWM modules to interactively control two kinds of LEDs. The resulted complex frequency of PWM has much shorter trigger time. Therefore, the deviations of color temperature at low duty cycle could be significantly reduced. The continuously-adjustable color temperature range of LED array is from 2800K to 4900K. An optical system was also setup to measure the illuminance and optical spectrum of the LED array simultaneously. The measured spectral information with various color temperature and illuminance could be used as a basis for qualifying the independent-adjustability of LED array. By using the developed driving method and calibration process, the deviation of color temperature and illuminance could be rapidly minimized. This technology provides a solution for precise optical lighting and related spectral applications.

2 EXPERIMENTAL SETUP AND WORKING PRINCIPLE

The experimental setup for color temperature, illuminance and spectrum measurement of the developed white light LED array is shown in Fig.1. The LED array is propped up by a metal plate and lighting down from top through a circle hole. The light beam is divergent and diffused by an optical diffuser, which has a thickness of 0.15 mm. The photographs of the front and rear side of the LED array are shown in the embedded pictures of Fig. 1. The LED array contains 12 × 8 pieces of white light LED chips. The 2800K and 4900K LEDs are equally divided and interlaced arranged. By adjusting the light contributions of two kinds of LED chips, the lighting with spectral-continuous color temperature could be achieved. The product models of the LED chips are SMD 5050 of 2800K and 4900K. The color temperature and luminous flux of the LED array could be manually or automatically controlled by the circuit board. Because the driving circuit using three PWM modules to interactively control two kinds of LED chips, the frequency of the PWMs have been mixed and generate a much shorter trigger time. Therefore, the adjustability, stability and precision of color temperature and luminous flux would much better than the traditional driving circuit that has only two PWM control modules (Prathyusha, 2004) (Montu and Regan, 2007) (David, et al., 2012). The divergent white light was partly collected by a chroma meter and a spectrometer. The instrument model of the chroma meter and spectrometer are CL-200A of Konica Minolta and SD1200 of OTO respectively. The receptor head of the chroma meter and integrating sphere of the spectrometer are both located near the center of the LED array in x-axis. The detection distance in z-axis between the LED array and sensing heads is about 60 mm.

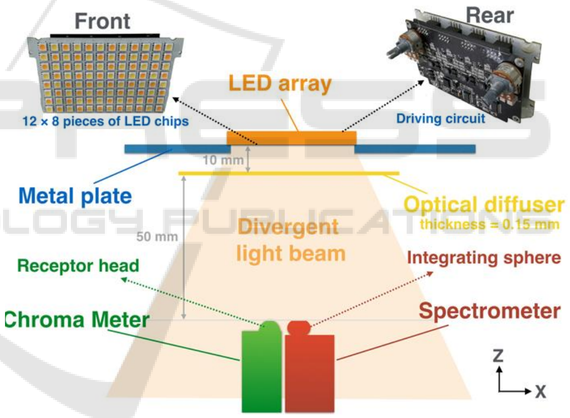

Figure 1: Experimental setup of the measurement system.

The working principle of three PWM is shown in Fig. 2. Traditionally, the color temperature of the LEDs can be arbitrarily regulated by means of two PWM controllers. As shown in Fig.2 (a) and 2(b), the PWM-1 and PWM-2 controlled the duty cycles of the 4900K and 2800K LEDs, respectively. The expected color temperature of the LED could be achieved by linearly combining the products of duty cycle and color temperature of two kinds of LEDs. However, This method has a drawback. The minimum duty cycle of PWM cannot be lower than the operation threshold of LED microcontroller. It means that the resolution for LED brightness adjustment will be limited. In other words, the color temperature and brightness will be roughly tied to each other. The solution of the problem is mixing a low-frequency PWM-3 with origin PWMs. The figure 2 (c) shows the spectrum of the PWM-3. The frequency is only 1kHz, which is one twentieth of PWM-1 and PWM-2. The figure 2 (d) and 2 (e) show that the new waveforms were accordingly generated by PWMs-mixing. As a result, the frequency of PWM becomes smaller and complex, which leads to the high-adjustability of the duty cycle. For a fixed luminance condition, the total pulse width per unit duty cycle is constant. Therefore, time of the single PWM become longer that could be effectively processed by the microcontroller. It means that the brightness and color temperature of the LEDs could be controlled in a more precise and flexible way.

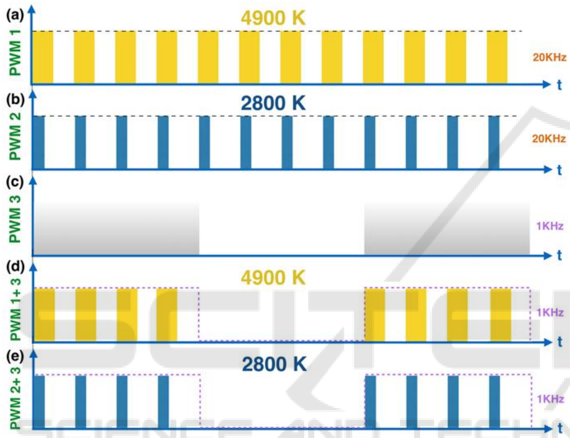

Figure 2: Working principle of the 3-pulse-width-modulation (PWM) control module.

In order to verify the efficacy of our developed LED array, two commercial LED products were selected for conducting the quality comparison. The item models of them are LL-162VT of Viltrox and PW-96LED of Paniko, respectively. Both of them are mixed LED array and designed for the photography application. In the measurement experiment, the chroma meter was first used to roughly measure the stability and adjustability of our developed LED array and these two typical products. Figure 3 shows the relationship between the measured color temperature and illuminance of the LL-162VT LED. The main feature of the LL-162VT is that the color temperature is non-adjustable and the luminous flux is adjustable. However, the measured result shows that the LED color temperature gradually increases with increasing illuminance. Although the labelled color temperature of this product is 5600K (Dashed blue line), all the measured data (Red curve) are less than this value in practice. The maximal percent deviation ratio of the color temperature is 3.13%. We believe that the result is good enough for the photography application because it is hard to distinguish such a small difference by the human eye.

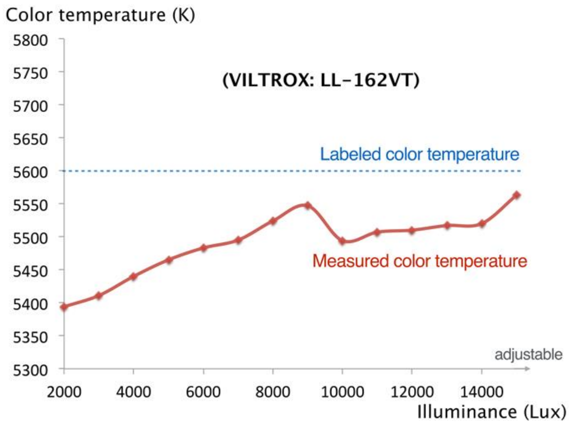

Figure 3: Deviations of the color temperature of a typical luminous-flux-adjustable product (LL-162VT).

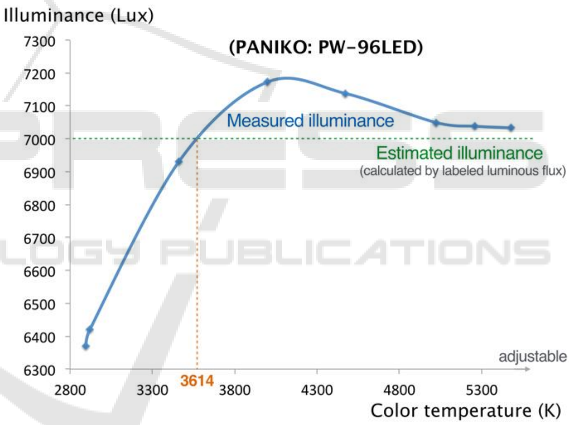

Figure 4: Deviations of the illuminance of a typical color temperature-adjustable product (PW-96LED).

Figure 4 shows the relationship between the measured color temperature and illuminance of the PW-96LED LED. The main feature of the LL-162VT is that the color temperature is adjustable and the luminous flux is non-adjustable. The estimated illuminance of this product is 7000 lux (Dashed green line), which is calculated by the labelled luminous flux. The measured result shows that the illuminance is much weaker than the labelled value when the color temperature is lower than 3614K. The illuminance becomes more stable when the color temperature is larger than 5000K. The maximal percent deviation ratio of the illuminance is 12.59%. It could be easily found that these two existing products have similar shortcomings: The changed illuminance always leads the change of color temperature, vice versa.

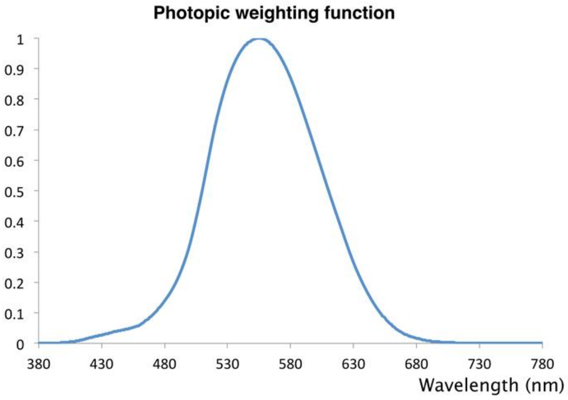

Figure 5: The photopic weighting function over the white light LED's spectral range.

In this study, the white light LED array using the developed 3-PWM control technology can overcome the problem described above, that is, either the adjustments of parameter will not obviously affect the other. The measured results of our LED device will numerically show in the next chapter. Furthermore, although the commercial chroma meter could quantify the color temperature and illuminance of LED array, the precision is much poorer than an optical spectrometer (or power meter). Accordingly, an optical spectrometer was subsequently used to finely measure the spectral distribution of our developed LED array. The purpose of this measurement is to know the power contribution at each wavelength of light. However, the quantity standard is different between the chroma meter and spectrometer. The measured unit of chroma meter is lux (illuminance), which belongs to photometric quantity. The measured unit of spectrometer is W/m^2 (irradiance), which belongs to radiometric quantity. The relationship between them can be written as follow:

$$E_v = 683 \cdot \int E(\lambda) \cdot V(\lambda) d\lambda \tag{1}$$

where $E(\lambda)$ is the irradiance, which could be measured by the spectrometer. The unit of irradiance at each wavelength is W/m^2/nm. The unit of total irradiance is W/m^2, which could be obtained by integrating the entire spectrum; E_v is the illuminance, which could be measured by the chroma meter. The operator of the $683 \cdot \int V(\lambda)\, d\lambda$ is photopic weighting function of human eye, as shown in Fig 5. The equation is obviously shows that the relationship between irradiance and illuminance. Therefore, the measured LED radiometric data could easily convert to the illuminance data. It means that the replacement of measurement instrument does not affect the result for the comparison.

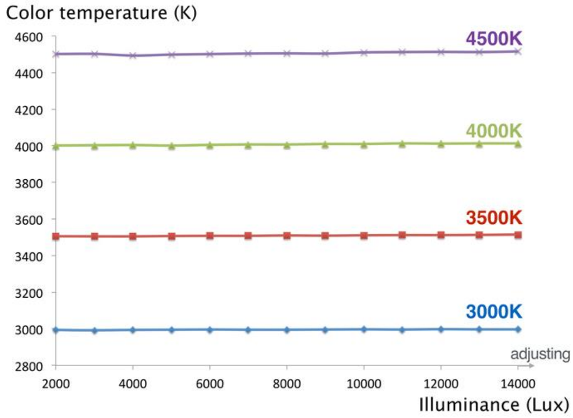

Figure 6: Deviations of the color temperature with increasing illuminance of the developed LED array.

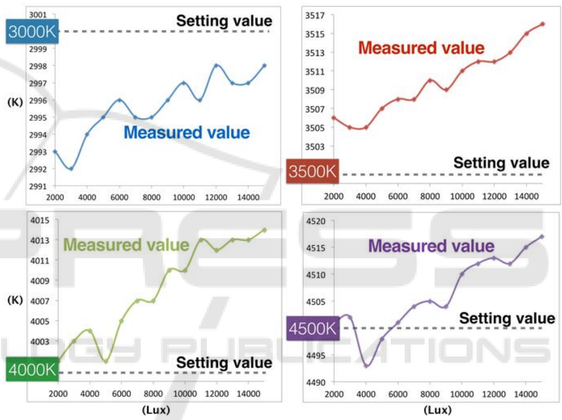

Figure 7: Enlarged view of the color temperature curves in Fig.6.

3 RESULTS AND DISCUSSION

The developed LED array using the 3PWM control technology could separately adjust the color temperature and luminous flux without influence on the other one. There are four kinds of color temperature, 3000k, 3500K, 4000K and 4500K, were created by mixing and adjusting the light contributions of 2800K and 4900K LEDs. In fact, the color temperature is continuously adjustable from 2800 to 4900K. Figure 6 shows the relationship between four color temperatures and illuminances of the developed LED array. It could be found that there is no significant change of the color temperature whatever the illuminance is. In fact, the changes are very slight and almost negligible. Figure 7 shows the enlarged picture for clearly discerning the change of each color temperature. A dotted grey line marked the setting value of each color temperature. Although the curves look dramatic changing, the amplitudes are very small. The average percent deviations of the color temperatures are only 0.15 % (3000K), 0.28 % (3500K), 0.2 % (4000K) and 0.17% (4500K), respectively. The result indicates that the stability of our developed LED array hardly deteriorate with the increasing color temperature. In other words, a luminous-flux-adjustable LED device with a constant color temperature was successfully achieved.

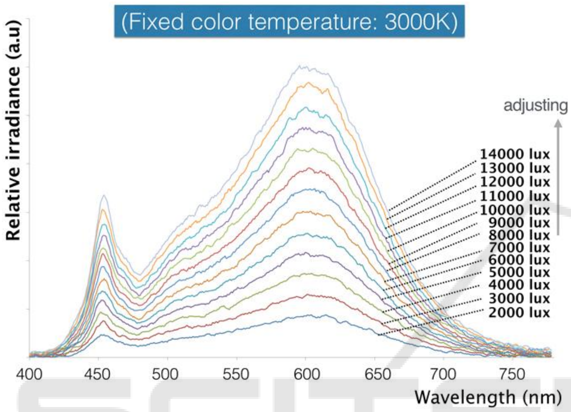

Figure 8: Measured spectra of the LED array with various illuminances at color temperature of 3000K.

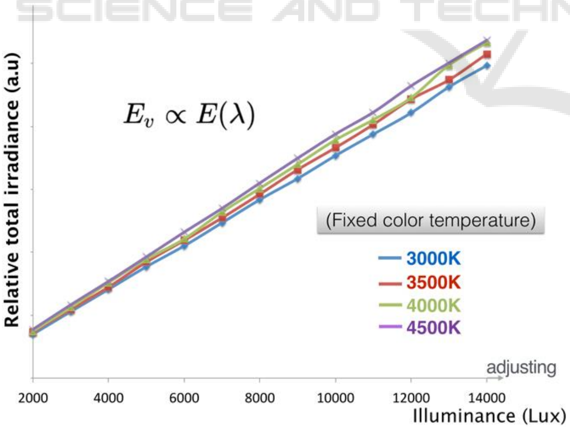

Figure 9: Relationship between relative total irradiance and illuminance at various color temperatures.

To understand the contribution of each wavelength, the optical spectrometer was used for the measurement. The color temperature is fixed at 3000K. The spectrum curves were captured at various illuminance of LED array. The measured result is shown in Fig.8. Because the white light LED is composed of blue light LED and yellow phosphor, the spectra have two obvious peaks. The axis of ordinate indicates the relative irradiance. Qualitatively, it is reasonable that the spectral curve become taller with the increase of LED illuminance. Quantitatively, the relative total irradiance could be obtained by integrating the curves. The optical spectra were individually measured at fixed color temperature of 3500K, 4000K and 4500K. The relationship between the estimated relative total irradiance and adjusted illuminance at various color temperature is shown in Fig. 9. It indicates that there is a proportional relationship between them. However, the slopes are slightly different. The reason is that the two parameters belong to different physical quantity. According to the equation (1), the relative irradiance should be weighted by the photopic function and integrated over the white light LED's spectral range. Then the calculated results would be comparable with the illuminance. Because the low color temperature light emitted by the LED array has more power contributions in red and yellow regime, the value of the integrated spectrum curve weighted by the photopic function would become larger. It means that the variation of illuminance would slightly larger than that of the relative total irradiance. Therefore, the slope would be relative smaller at lower color temperature.

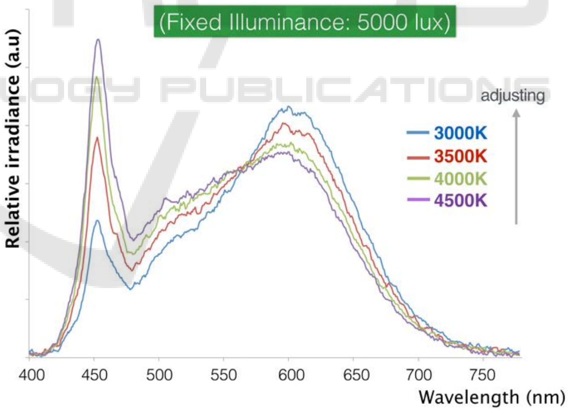

Figure 10: Measured spectra of the LED array with various color temperature at fixed illuminance of 5000 lux.

On the other hand, the developed LED array should also have the color-temperature-adjustable characteristics without influence on the luminous flux. This time, the luminous flux of LED array is fixed and the spectrum curves were captured at various color temperature. Although we had in fact measured seven sets of spectra from 2000 to 14000 lux, only the spectra at 5000 and 8000 lux are shown in this paper as the representatives. Figure 10 and 11 shows the measured spectra of the LED array with various color temperature at fixed illuminance of 5000 and 8000 lux, respectively. The spectral distributions and relations are similar to each other. Both figures indicate that lower color temperature light emitted by the LED array has more power contributions in red and yellow regime, and fewer contributions in blue regime. If the developed LED array has the advantage of stable luminous flux whatever the color temperatures, the values calculated by integrating the spectrum curves weighted by the photopic function must be nearly equal to each other. To demonstrate this characteristic, the spectrum curves in Fig. 10 and Fig. 11 were first weighted by the photopic function (Fig. 5). The corresponding results are shown in Fig. 12 and Fig. 13, respectively. Due to the unit converting, the axis of ordinate becomes relative illuminance from relative irradiance. It could be found that the contributions of LEDs in blue regime have been substantially weakened because the human eye is less sensitive to blue light. The larger contributions are generated from the region of wavelength between 520 and 620 nm. Then, the values of relative total illuminance could be obtained by integrating the curves in Fig. 12 and 13. The percent deviation of total illuminance of each value could be subsequently estimated. The tables embedded in Fig. 12 and 13 shows the accordingly results. When the reference is defined as the relative total illuminance value at 3000K, the maximal percent deviations are less than 1.35% at 5000 lux and 7.6% at 8000 lux, respectively. The results indicate that the change of color temperature affect slightly the illuminance. Therefore, the stability of the luminous flux of the color-temperature-adjustable LED array is numerically better than that of the existing products.

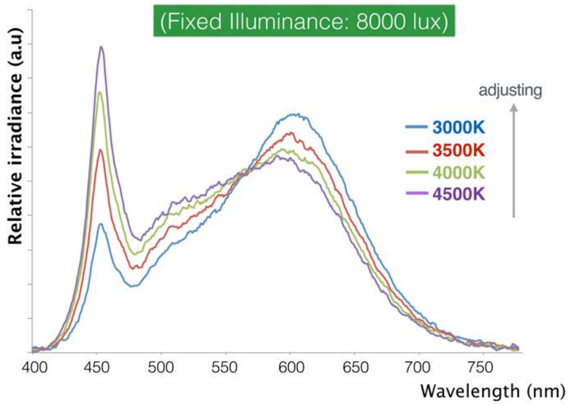

Figure 11: Measured spectra of the LED array with various color temperature at fixed illuminance of 8000 lux.

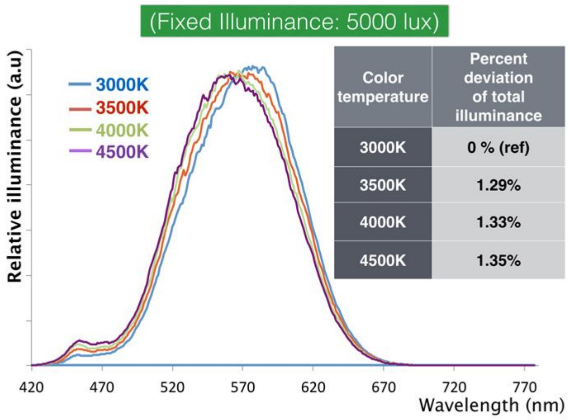

Figure 12: Spectrum curves weighted by photopic function with various color temperature at fixed illuminance of 5000 lux.

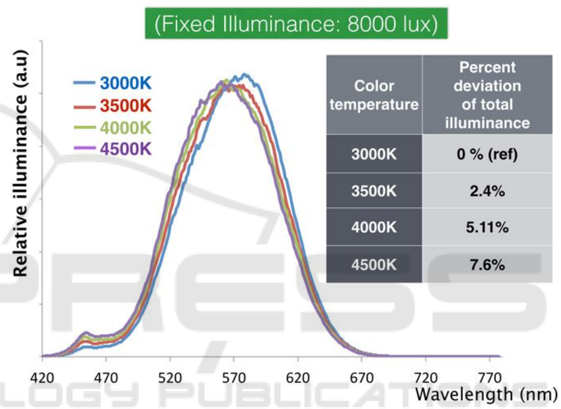

Figure 13: Spectrum curves weighted by photopic function with various color temperature at fixed illuminance of 8000 lux.

Figure 14 shows the suggested classification of LED array, calibration of measurement system and possible applications. Because the operation of chroma meter is simple, rapid and high compatible with environments, the color temperatures and illuminances of the tuneable white light LED array could be first measured. In this step, the poor-stability ones would be classified and applied to the daily lighting because the general people's tolerance for color temperature variety is relatively high. Optical spectrometer has much better precision than the chroma meter, and could subsequently provide the power contribution at each wavelength. The better-stability LED array could be applied to the professional visual domain, such as photography, display manufacturing and color management. Finally, the best-stability LED array qualified strictly by the spectrometer could be applied to the research domain, especially in spectral optics, sample excitation, photochemical reactions and bio-optical response. Furthermore, the spectrometer could calibrate the optical source, even the LED array equipped with various optical filters, such as bandpass filter, polarizer and attenuator. The radiometric and photometric quantities could be freely converted by using the Eq. (1). After performing the calibration, the LED array driven by 3-PWM control modules would provide the best adjustability, precision and stability.

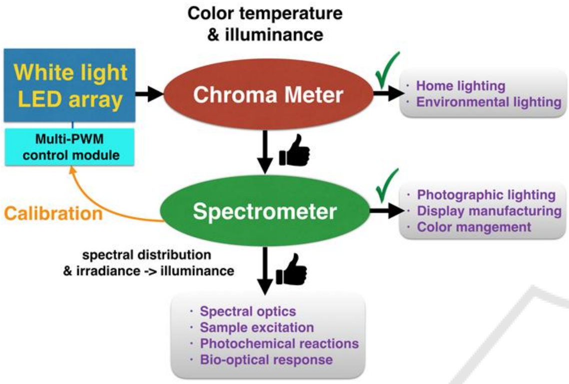

Figure 14: Suggested procedure for the LED classification and optical system calibration.

4 CONCLUSIONS

This study succeeded in developing a 3-PWM control module that can separately adjust the color temperature and luminous flux of a white light LED array. The breakthrough is that either the adjustments of parameter will not obviously affect the other one. The color temperature of the LED array is continuously adjustable by mixing and adjusting the light contributions of 2800K and 4900K LED chips. An optical measurement system composed of a chroma meter and optical spectrometer was set up. The measured results show that the average percent deviations of the color temperatures are at least smaller than 0.28%, in spite of the illuminance of LED array. With the converting of radiometry and photometry quantity, the measured integrated spectra weighted by photopic function can be treated as a reference of illuminance. For the adjustment of color temperature with a fixed illuminance, the percent deviations of the illuminance are between 1.35% and 7.6%. Therefore, the developed LED array equipped with the 3-PWM control module is numerically better than that of the existing commercial products. The LED driving circuit concept, measurement procedure and analysis method are compatible with various kinds of white light LED. We believe that this study provides a new solution and applications for white light LED lighting technology.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation for financial aid from the Ministry of Science and Technology, R.O.C under grant numbers 104-2622-B-492-001-CC3. The authors would also like to express their gratitude to the Instrument Technology Research Center of National Applied Research Laboratories for the support.

REFERENCES

Nadarajah, N., Yimin G., 2005. Life of LED-Based White Light Sources. *Journal of Display Technology*, Vol. 1(1), pp. 167-171.

Ye, S., Xiao, F., Pan, Y.X., Ma, Y.Y., Zhang, Q.Y., 2010. Phosphors in phosphor-converted white light-emitting diodes: Recent advances in materials, techniques and properties. *Materials Science and Engineering*, Vol. 71(1), pp. 1-34.

Ingo, S., Marc, S., 2006. Color temperature tunable white light LED system. *Proc. SPIE*, p. 6337.

Sheu, J. K., Chang, S. J., Kuo, C.H., Su, Y. K., Wu, L.W., Lin, Y. C., Lai, W. C., Tsai, J. M., Chi, G. C., Wu, R. K., 2003. White-light emission from near UV InGaN-GaN LED chip precoated with blue/green/red phosphors. *IEEE Photonics Technology Letters*, Vol. 15(1), pp. 18-20.

Yoshi, O., 2005. Spectral design considerations for white LED color rendering. *Opt. Eng.*, Vol. 44(11), p. 111302.

Guoxing, H., Huafeng, Y., 2011. Optimal spectra of the phosphor-coated white LEDs with excellent color rendering property and high luminous efficacy of radiation. *Optics Express*, Vol. 19(3), pp. 2519-2529.

Guoxing, H., Lihong Z., 2010. Color temperature tunable white-light light-emitting diode clusters with high color rendering index. *Applied Optics*, Vol. 49(24), pp. 4670-4676.

Jung-Chieh, S., Chun-Lin L., 2009. Color temperature tunable white light emitting diodes packaged with an omni-directional reflector. *Optics Express*, Vol. 17(24), pp. 21408-21413.

Elodie, M., Jean-Jacques, E., F, Viénot., 2009. Testing LED lighting for colour discrimination and colour rendering. *Color Research & Application*, Vol. 34(1), pp. 8-17.

Prathyusha, N., D.S, Z., 2004, An effective LED dimming approach. *Proc. IEEE Ind. Appl. Conf.*, pp. 1671-1676.

Montu, D., Regan, Z., 2007. Digital Architecture for

Driving Large LED Arrays with Dynamic Bus Voltage Regulation and Phase Shifted PWM. *Proc. IEEE Appl. Power Electron. Conf. (APEC), pp.* 287-293.

David, Gacio., J. Marcos, Alonso., Jorge G., Lidia C., Mario, J. C., Manuel R-S., 2012. PWM series dimming for slow-dynamics HPF LED drivers: The high-frequency approach. *IEEE Trans. Ind. Electron.*, Vol. 59(4), pp. 1717-1727.