# Application-Specific Spectral Power Distributions of White Light

Po-Chieh HUNG＊, Konstantinos PAPAMICHAEL＊＊

## Abstract

We report on the potential of today's LED technologies to approximate Spectral Power Distributions (SPDs) aimed at optimizing specific performance goals. We compare numerically optimal SPDs to actual SPDs produced by a 16-channel LED light source, aiming at optimizing performance for six different applications. These theoretical and practical limits of the potential of current LED technologies can serve as guidelines for the design of future LED sources for different applications.

## 1 Introduction

The advent of LED technologies is providing significant freedom in designing white light sources with customized Spectral Power Distributions (SPDs). While there are still limitations in producing optimized SPDs for different applications, new advancements in LED, quantum dot and micro-cavity technologies hold promise to reaching fully optimized SPDs in the future.

Optimized SPDs depend on luminous performance goals. A typical application example is general lighting, where the performance goal is to reproduce colors with minimum energy consumption as if the objects were illuminated by natural light sources such as daylight or blackbody radiation. Hung and Tsao derived numerically optimized SPDs for this purpose considering various Correlated Color Temperatures (CCT) and Color Rendering Index (CRI) values. They found that the maximum Luminous Efficacy of Radiation (LER) is achieved with CCT ranging between 2400K and 3000K at a CRI less than 95 [1]. Also Hung extended this idea to other specific white light performance goals, such as color gamut, impact on artifacts, high and low impacts to ipRGC, light used in semiconductor manufacturing facilities, and also examined the impact of specialized SPDs on image capturing systems [2].

In this paper we report on the potential of today's LED technologies to approximate optimal SPDs of white light, considering six different luminous performance goals: 1) maximum LER, 2) maximum color gamut, 3) maximum impact on ipRGC, 4) minimum impact on ipRGC, 5) minimum impact on museum objects, and 6) no power below 500 nm.

---

＊Konica Minolta Laboratory U.S.A. Inc.
＊＊California Lighting Technology Center, University of California, Davis

## 2 Approach

Using computer simulations and evaluation functions for each performance goal, we determined numerically optimal SPDs (optimal light, hereafter) for each performance goal. The evaluation functions were defined by the desired spectral sensitivity for each performance goal. The numerically optimal SPDs were determined by setting SPD as a variable and applying non-linear optimization using Solver in Microsoft Excel. We then used a TeleLumen Light Replicator system with sixteen LED sources (Figure 1), to approximate the numerically optimal SPDs for the six different performance goals (LED light, hereafter). We also used the blackbody SPD within 380 nm and 780 nm that produces the same CCT as a performance benchmark (blackbody light, hereafter). CCT, CRI and allowance for $D_{uv}$ were chosen depending on performance goal. Note that CRI and $D_{uv}$ for blackbody light is always 100 and zero, respectively. Also, although the definition of CRI requires switching the reference light source between blackbody and daylight at 5000K, we used only blackbody SPD for simplification.

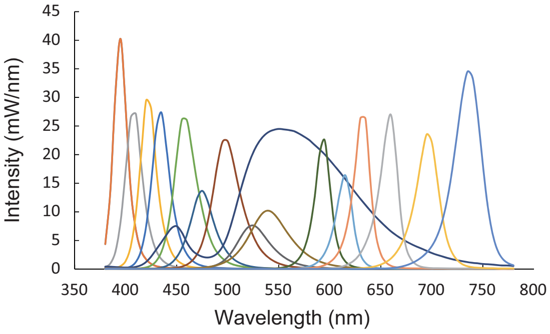

Fig. 1 SPDs of the Telelumen Light Replicator LEDs.

## 3 Application and optimized SPD

Numerically optimal LED lights were computed for the six applications considered. Here, CRI means $R_a$, unless noted. In figures, the luminance of each light is normalized to be equal among graphs except for Figure 1. The heights of wanted spectrum (long dotted line) and unwanted spectrum (short dotted line) are arbitrary.

Maximum Luminous Efficacy of Radiation: Assuming that the ultimate goal of lighting is to let people see colored objects with the minimum amount of energy consumption, we used the LER as the evaluation function under the condition of a CCT of 2856K, a CRI of 90, and a $D_{uv}$ of zero, without considering $R_9$. The resulting LERs for optimal, LED and blackbody lights are 410, 379, and 154 lm/W, respectively. Optimal light consists of four peaks while LED light consists of three peaks (Figure 2). As the result, $R_9$ values of numerically optimal and LED lights are 0 and 10, respectively.

We also considered the combination of CRI=90 and $R_9$=50, which represent the minimum requirements of California Lighting Quality Specification [3], which resulted to a slight drop in numerically optimal and LED LERs to 404 and 369 lm/W, respectively (Figure 3, upper). In contrast, the combination of CRI=80 and $R_9$=0, which represent the minimum requirements for Energy Star [4], resulted in numerically optimal and LED LERs of 421 and 378 lm/W, an increase from the California standard of 4% and 2.4% respectively (Figure 3, lower). This indicates that better color quality can be achieved with very small LER penalty.

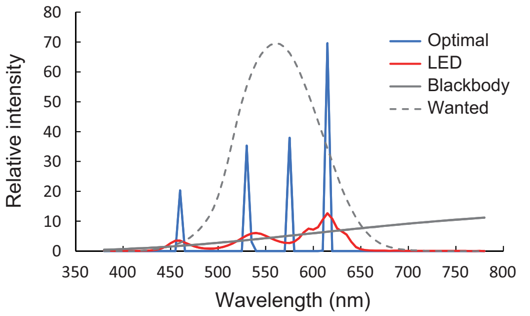

Fig. 2 Example optimized SPD for maximum LER without consideration of $R_9$.

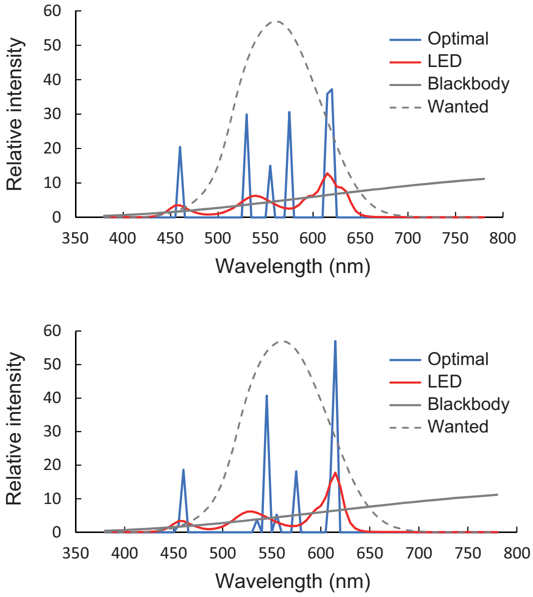

Fig. 3 Example optimized SPD for maximum LER with other parameters. Upper: CRI=90 and $R_9$=50, lower: CRI=80 and $R_9$=0.

Maximum Color Gamut: In certain applications, such as meat and fruit displays in grocery stores, it is desired to enhance color saturation to make objects appear more attractive. Today this is practiced with fluorescent lamps that are available in the market [5]. The evaluation function for this performance goal aimed at maximization of color gamut. The function was determined by calculating the area in the u'v' chromaticity diagram that corresponds to the eight color patches used in CIE 13.3 [6], considering a CCT of 5000K and a $D_{uv}$ of zero. Under these conditions, the areas of color gamut for numerically optimal and LED lights were 179% and 156% of the blackbody light, respectively (Figure 4). In practice, a moderate level of color saturation will be preferred rather than the extreme maximization considered in this study, which will make colors of objects appear unnatural.

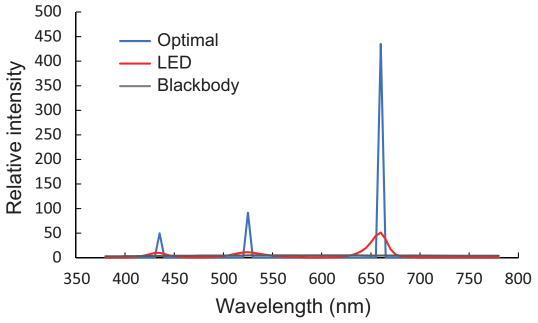

Fig. 4 Example optimized SPD for maximum color gamut.

Maximum Impact on ipRGC: Maximum impact on ipRGC per luminance is desired as “wake-up” light in spaces such as meeting rooms, offices, and airplanes crossing multiple time zones. While there is still no agreement on exact spectrum for ipRGC impact, we use Brainard’s data [7] with a smooth curve fitting, expressing the impact on ipRGC per luminance. As the impact on ipRGC increases with higher CCT light, we considered a CCT of 6500K along with a CRI of 90 and a $D_{uv}$ of zero (Figure 5). The impact of numerically optimal and LED lights is 131% and 118% against blackbody light, respectively.

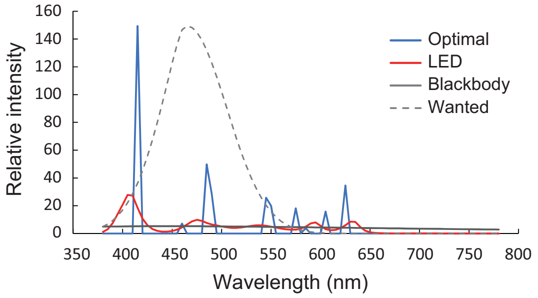

Fig. 5 Example optimized SPD for maximum impact on ipRGC.

Minimum Impact on ipRGC: Minimum impact on ipRGC is desired for night light to avoid disturbance of circadian rhythms or for light used in the cockpit of vessels and airplanes at night, where it helps to keep the pupil dilated facilitating seeing objects in outside dark conditions as well as in the cockpit. Here the evaluation function is the impact on ipRGC per luminance. As the impact on ipRGC decreases with lower CCT light, we used a CCT of 2856K and a CRI of 50. The impact of the numerically optimal and LED lights is 42% and 98% against blackbody light, respectively (Figure 6). Current LED technologies cannot provide significantly better results compared to blackbody light because of lack in peak wavelength in the 560-570nm region. However, both numerically optimal and LED lights give a better LER: 401 and 317 lm/W, while blackbody light gives 154 lm/W.

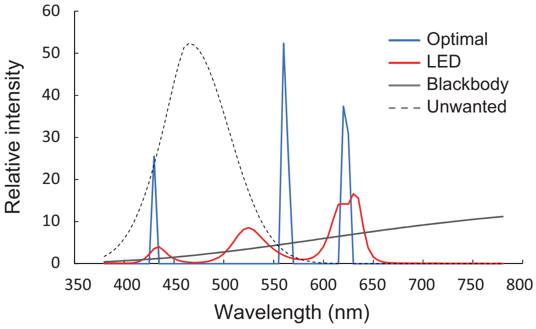

Fig. 6 Example optimized SPD for Minimum impact on ipRGC.

Minimum Impact on museum objects: Preventing light-caused fading of museum objects, such as paintings, is one of the most important considerations in museum and gallery lighting. We used one of the hazardous light spectra specified in CIE 157 [8] to define the numerically optimal SPD and minimize the hazardous part per luminance under a CCT of 4000K, a CRI of 95, and a $D_{uv}$ of zero. The impacts of numerically optimal and LED lights are 57% and 64% against blackbody light (Figure 7). Obviously lower CCT values will give better results in terms of preservation, but at the expense of color rendition.

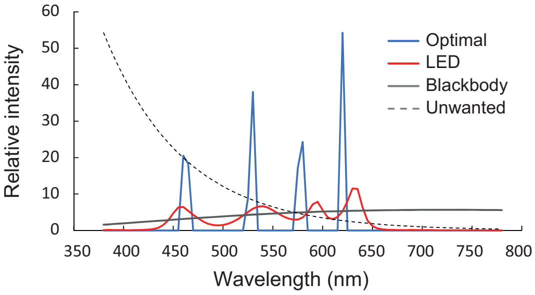

Fig. 7 Example optimized SPD for minimum impact on museum objects.

No Power below 500 nm: Short wave radiation below 500 nm is not desired during the manufacturing process of semiconductors in photolithography cleanrooms, because of negative effects of ultraviolet and blue light on photoresists. Thus yellow light, generated by fluorescent and yellow sharp-cut filters, is often used for lighting, which has extremely low CRI that makes workers feel uncomfortable. We considered an optical sharp-cut filter that eliminates radiation shorter than 500 nm to cut off the blue part of the spectrum, with a CCT of 2000K and a maximum $D_{uv}$ of 0.005. The numerically optimal light achieves CRI of 45 for $R_a$ and 20 for $R_9$, at LER of 366 lm/W. LED light can achieve a CRI of 45 for Ra and 75 for $R_9$ but with LER at 236 lm/W, while Blackbody light is only 94 lm/W (**Figure 8**).

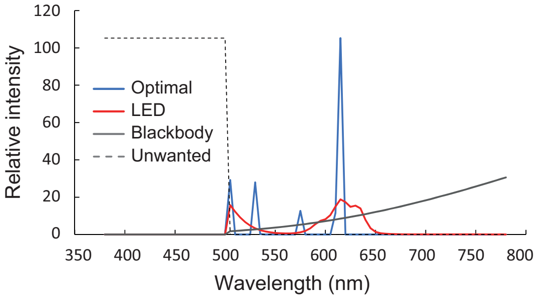

Fig. 8 Example optimized SPD without power below 500 nm.

Input values used to create these LED lights and their CCT, CRI ($R_a$ and $R_9$) and LER except **Figure 3** are shown in Table 1. The highest value is normalized to be one. Note that the white LED made by blue LED and phosphor and some of LEDs were not used eventually.

Table 1 Input values to create LED lights.

| Peak wavelength (nm) | Maximum luminous efficacy of radiation | Maximum color gamut | Maximum impact on ipRGC | Minimum impact on ipRGC | Minimum impact on museum objects | No power below 500 nm |
|---|---|---|---|---|---|---|
| 395 | - | - | 0.149 | - | - | - |
| 405 | - | - | 1.000 | - | - | - |
| 425 | - | 0.039 | - | - | - | - |
| 435 | - | 0.183 | - | 0.135 | - | - |
| 455 | 0.195 | - | - | - | 0.380 | - |
| 475 | 0.005 | - | 0.688 | - | 0.087 | - |
| 495 | - | - | 0.107 | - | - | 0.872 |
| 525 | - | 0.772 | - | 1.000 | 0.121 | - |
| 540 | 0.875 | - | 0.565 | 0.044 | 1.000 | - |
| white | - | - | - | - | - | - |
| 595 | 0.323 | - | 0.325 | - | 0.499 | 0.200 |
| 615 | 1.000 | - | - | 0.598 | 0.042 | 1.000 |
| 635 | 0.265 | - | 0.326 | 0.527 | 0.701 | 0.521 |
| 660 | - | 1.000 | - | - | - | - |
| 695 | - | - | - | - | - | - |
| 735 | - | - | - | - | - | - |
| CCT | 2856 | 5000 | 6500 | 2856 | 4000 | 2000 |
| $R_a$ | 90.0 | 16.5 | 90.0 | 50.0 | 95.0 | 45.0 |
| $R_9$ | 10.4 | -316.3 | 95.4 | 0.0 | 91.9 | 75.2 |
| LER | 379 | 166 | 193 | 317 | 341 | 236 |

## 4 Discussion

All numerically optimal SPDs in this study represent bright line (spiky) spectra. This implies that future lighting would probably be realized by combinations of monochromatic lights, such as LEDs, to achieve the best effect for specific application. Realizing such spectra requires further development of materials and systems. Ideally light sources should be able to combine peak wavelengths and bandwidths without speckles. We may need to wait for such light sources, but as shown in this paper, current LED technology can achieve semi-optimized results. Among the six applications we considered, one exception is the application for minimum impact on ipRGC. Due to lack of appropriate green LEDs, the impact on ipRGC is almost equal to blackbody light.

An important issue in using bright line spectra is the effect to human vision. It is known that color matching functions slightly differ among individuals. Thus such spectra may cause differences in color appearance. Bright line spectra would be definitely problematic for color image capturing devices, such as digital cameras, because of variation of spectral sensitivity, but may be acceptable by human vision in specific applications [2]. We need further studies to better understand acceptability in difference applications.

Another important issue is the evaluation of such optimized light sources. In this report, the current CRI recommended by CIE is used as color quality metric. However it is well known that the current version of CRI ($R_a$), considering only eight color samples, has limitations, especially for such extreme SPDs. One immediate solution may be choosing typical colors in specific application environments for the calculation of Special Color Rendering Index as defined in CIE 13.3. Currently CIE TC 1-90 is working on a new CRI version, which resolves some of the main issues of the current version.

The white light considered in this study was on the Planckian locus. However, it has been reported that preferred white light might be located off the Planckian locus [9]. This factor should also be considered in detailed design of SPDs.

## 5 Conclusion and Future Work

We developed and demonstrated optimized SPDs for six specific luminous performance goals, using numerically optimal SPDs and their approximation using a sixteen channel LED tunable light source and reported on numerically optimal and actual LED performance considering six different luminous performance goals. The results seem very promising in terms of producing customized spectra for difference applications.

## 6 References

[1] P.-C. Hung and J. Tsao, Maximum White Luminous Efficacy of Radiation versus Color Rendering Index and Color Temperature: Exact Results and a Useful Analytic Expression, J. of Display Technology, 9(6), 405 - 412 (2012).

[2] P.-C. Hung, Extreme Spectral Power Distribution of Light Source and its Impact to Human Vision and Cameras Sensitivity, the 21st Color and Imaging Conference, 33-38 (2013).

[3] G. Flamm, O. Howlett, and G. D. Taylor, Voluntary California Quality Light-Emitting Diode (LED) Lamp Specification, California Energy Commission, High Performance Buildings and Standards Development Office, 2012. (http://www.energy.ca.gov/2012publications/CEC-400-2012-016/CEC-400-2012-016-SF.pdf).

[4] “Light Bulb Key Product Criteria,” ENERGY STAR. U.S. Environmental Protection Agency and U.S. Department of Energy, n.d. Web. 9 March 2015 (https://www.energystar.gov/index.cfm?c=lamps.pr_crit_lamps).

[5] http://page.cextension.jp/c3905/pageview/pageview.html?page_num=87#_ga=1.30013759.1899892748.1442397700(in Japanese).

[6] “Method of measuring and specifying colour rendering properties of light sources,” Commission Int. de l’Eclairage, Vienna, Austria, Publication 13.3, 1995.

[7] G. C. Brainard, J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner, and M. D. Rollag, Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor, J. of Neuroscience, 21(16), 6405-6412 (2001).

[8] “Control of damage to museum objects by optical radiation,” Commission Int. de l’Eclairage, Vienna, Austria, Publication 157, 2004.

[9] M. S. Rea and J. P. Freyssinier, White lighting, Color Research & Application, 38(2), 82-92 (2013).

## Source

This paper is reprinted with minor revision of “SID International Symposium Digest of Technical Papers, Vol. 48 (2015).”