Optimal Ways of Color Mixing for High-Quality White-Light LED Sources

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White-light sources suitable for solid-state lighting are required to provide, on the one hand, good color rendition usually estimated in terms of color rendering index (CRI) and, on the other hand, high efficacy dependent on both the integral emission spectrum of the light source and efficiency of electricity-to-light conversion. Simultaneous achievement of maximum CRI and efficacy is rather problematic because of the well-known trade-off between these parameters [1]. Therefore, finding a compromise in the choice of CRI and efficacy suitable for particular applications is necessary by applying one or another criterion. Normally luminous efficacy of radiation (LER) is considered instead of the actual device efficacy in order to simplify optimization of light mixing. Our paper reports on the simulation study of light mixing regarding the efficacy as the central point of the optimization along with CRI of white light.

We have studied two types of the white-light source. One is comprised of LEDs only, whereas another utilizes partial conversion of light emitted from a blue LED by a yellow YAG:Ce^{3+} phosphor. Being focused on achievement of CRI > 90, we considered nitride (both blue and green) and phosphide (red) LEDs as those suitable for producing high-quality white light. Asymmetric emission spectra of every type of LED with the half-widths dependent on the peak emission wavelength and the YAG phosphor emission curve were parameterized using available data. Experimental maximum wall-plug efficiencies (WPEs) of nitride and phosphide LEDs as a function of the emission wavelength were also borrowed from literature to use in the simulations.

In our study we have considered white light metameric to the black-body radiation. The peak emission wavelengths of individual LEDs, the number of LEDs, and the power fractions of the LED spectra in the total spectrum of white-light were varied by a specially designed optimizer to find the values providing simultaneous maxima in CRI and LER. Then the effective WPE of the white-light source was estimated from the WPEs of individual LEDs and the resulting efficacy of the source was calculated. In the case of the YAG phosphor, its effective WPE was calculated with the account of the Stokes shift by using its emission spectrum and that of the blue LED pumping the phosphor and thus participating in the light conversion.

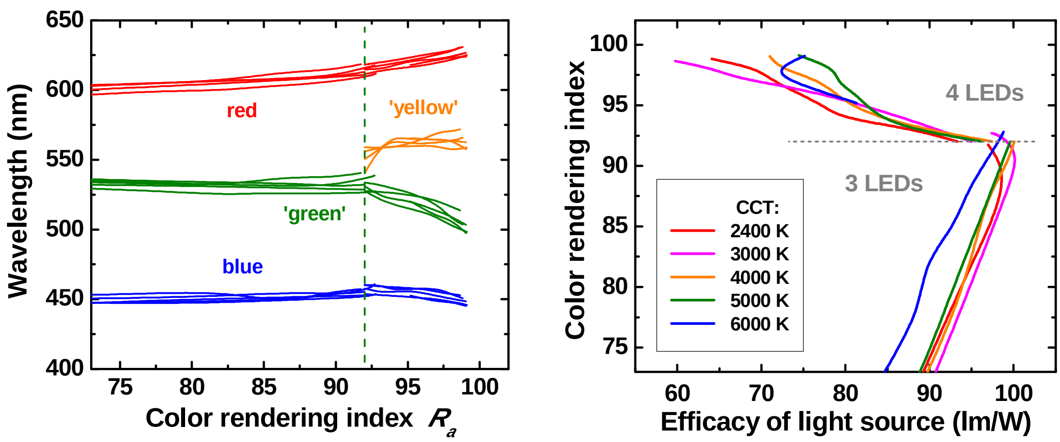

Fig.1 Optimal emission wavelengths as a function of maximum CRI value (left) and maximum CRI *versus* maximum efficacy of the white-light source comprised of LEDs only (right). Different lines correspond to various CCT values from 2400 to 6000 K.

Optimal peak emission wavelengths as a function of maximum CRI obtained by optimization of color mixing in the light source containing only LEDs are shown in Fig.1. The wavelengths are found to depend weakly on CCT, which is in line with the results reported earlier for “monochromatic” four-color light sources [2]. Optimal color mixing for CRI < 92 is achieved with three LEDs, whereas CRI > 92 requires four LEDs for getting high-quality white light. On the other hand, the maximum efficacy of ~100 lm/W can be attained only with three LEDs, since the use of four LEDs results in dramatic reduction of the efficacy (Fig.1).

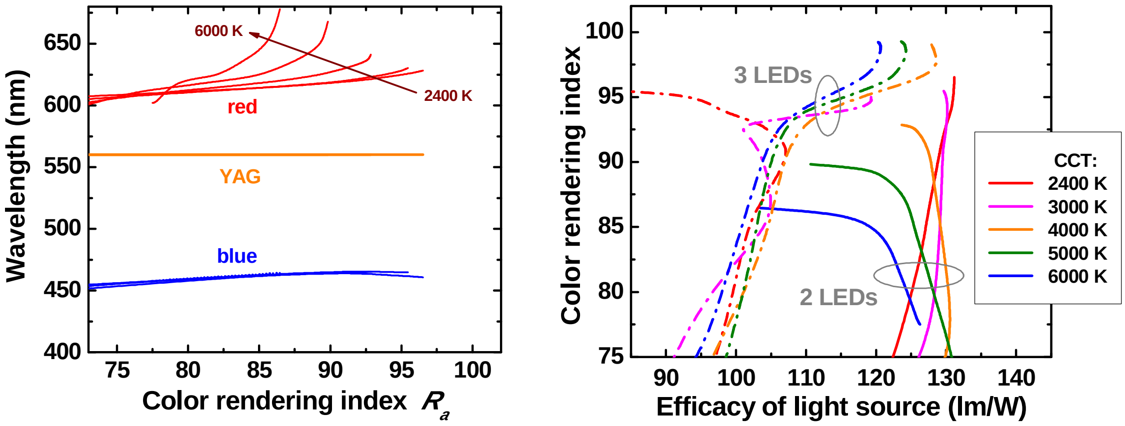

Fig.2 Optimal emission wavelengths as a function of maximum CRI value (left) and maximum CRI *versus* maximum efficacy of the source utilizing partial light conversion by YAG phosphor (right). Different lines correspond to various CCT values from 2400 to 6000 K.

In the case of the light source utilizing partial light conversion by the YAG phosphor, the optimal peak wavelengths depend substantially on desirable CCT (Fig.2). Correspondingly, the optimal ways of color mixing are also found to be CCT depending. For the warm white light with CCT = 2400-3000 K, the maximum efficacy of ~130 lm/W can be reached at CRI ~95-96 by using two LEDs and the YAG phosphor. In contrast, efficacy of ~120-125 lm/W at CRI ~97-98 is predicted for three LEDs and the phosphor in the range of CCT = 4000-5000 K (Fig.2). These two alternative solutions may suit different applications.

Comparison of the considered light sources shows the solution utilizing partial light conversion to be advantageous from the point of view of the maximum efficacy and CRI achieved. The reason for this is a higher effective WPE of the YAG phosphor compared to WPE of the green LED which lies in the so called ‘green gap’ of the LED efficiency.

The paper will also consider the potential for WPE improvement of individual LEDs and, hence, of the efficacy of the white-light source. Opportunities for development of the light sources with variable CCT will be discussed as well.

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References

[1] A. Žukauskas, R. Vaicekauskas, F. Ivanauskas, R. Gaska and M. S. Shur, *Appl. Phys. Lett.* **80**, 234 (2002).

[2] J. Y. Tsao, M. E. Coltrin, M. H. Crawford, and J. A. Simmons, Proc. IEEE **98**, 1162 (2010).