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LED-based white light

Les sources de lumière blanche à base de LED

Aurélien David [a,*], Lorne A. Whitehead [b]

[a] *Soraa Inc., 6500 Kaiser Dr., Fremont, CA 94555, USA*
[b] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada*

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ABSTRACT

This article discusses the use of light-emitting diodes to generate white light – a research forefront in Physics and Ergonomics. We first present various technological approaches to white-light generation. After a general introduction to the human vision system, we discuss two key aspects of the quality of white light: the color of the light itself, and the color rendering of illuminated objects. We present the tools underlying modern color science, and review key color rendering metrics, from the well-known color rendering index to the latest improvements in the field.

RÉSUMÉ

Cet article présente l'utilisation des diodes électroluminescentes comme sources de lumière blanche – un sujet à la pointe de la recherche en physique et en ergonomie. Nous présentons d'abord diverses approches technologiques à la génération de lumière blanche. Après une introduction générale au système visuel humain, nous discutons deux aspects cruciaux de la qualité de la lumière : la couleur intrinsèque de celle-ci et le rendu des couleurs des objets illuminés. Nous présentons les outils sous-jacents à la colorimétrie moderne, et examinons les principales métriques du rendu des couleurs : le CRI, ainsi que les derniers progrès dans le domaine.

1. Introduction

A significant portion of the world's energy consumption is used to generate white light to enable vision when daylight is not available. The first artificial illumination, firelight, predates history, and electric light has been common for over 100 years, so one might expect that all the relevant technical and physiological factors involved would by now be completely

* Corresponding author.
E-mail address: aurelien.david@polytechnique.org (A. David).

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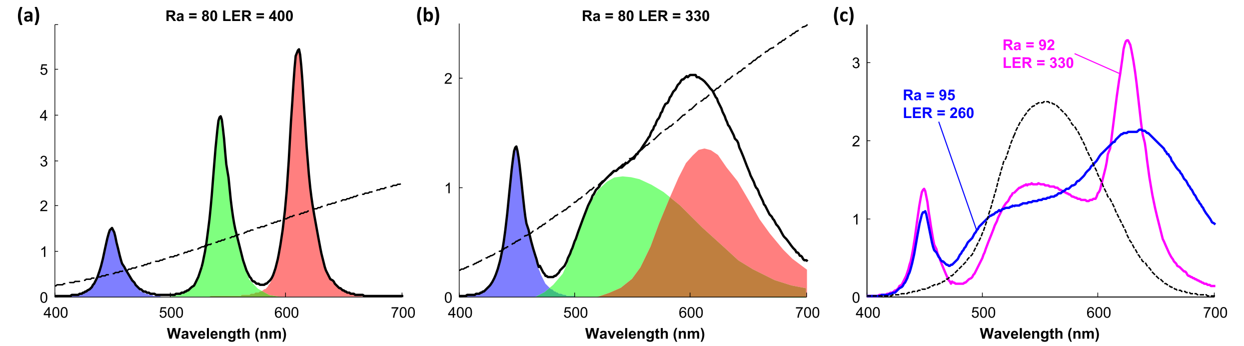

Fig. 1. SPDs of white LEDs, each with a correlated color temperature (CCT) of 3000 K and producing the same amount of lumens (the vertical axis is in arbitrary units). (a) Combination of blue, green and red LEDs: the black line is the composite LED SPD. The dashed line is the blackbody radiator of same CCT. (b) Same as (a), but for a blue-pump LED exciting green and red phosphors. (c) Dotted black line: photopic sensitivity curve $V(\lambda)$. Blue and magenta lines: two high-CRI LED SPDs (blue: using a standard red phosphor; red: using a narrow red quantum-dot). The two SPDs have similar R_a, but the latter has a much higher LER, since it emits little far-red radiation.

understood. Yet, that is not fully the case: researchers are not yet sure what light sources best meets the needs of users in various situations, and the design freedom offered by light-emitting diodes (LEDs) exacerbates this shortfall.

This article presents the status and recent developments of LED white light sources. We first discuss the technologies enabling LED-based generation of white light. We then introduce basic concepts in color science and discuss the challenges of producing white light that has high quality from an ergonomic perspective. We conclude with a discussion of needed future research on illumination.

2. How do we make white light?

LED chips emit radiation within a narrow wavelength range (10–25 nm) with energies close to that of the semiconductor bandgap. This contrasts with conventional light sources such as daylight and filament lights, which are approximately blackbody radiators with broadband emission. Therefore, LED spectra must be combined or modified to obtain white light. Two main technological approaches can be employed to this effect: combining multiple LED emitters, and down-conversion by phosphors.

In the following, we use the term Spectral Power Distribution (SPD) to describe a light source's distribution of intensity as a function of wavelength.

2.1. Combining LEDs

In this approach, several narrow-band LEDs have their light outputs blended to achieve white light. A common approach is to combine three kinds of LEDs, emitting in the blue, green and red ranges, as illustrated in Fig. 1(a). The relative power of these LEDs is selected to yield a desired chromaticity (see Section 3.2) for the blended light. An advantage of this approach is that it avoids creating light at unwanted wavelengths, since each emitter is narrow spectrally. Another is that the power for each LED color can be varied to tune the resultant chromaticity.

However, this approach creates several practical challenges. First and most importantly, materials are currently not available to make highly-efficient LEDs at all wavelengths. The III-Nitride material system excels in the blue range, but its efficiency is lower for green emission and very poor in the yellow range (in fact, the best green emitters today use a blue LED to pump a green phosphor). The "legacy" AlInGaAsP material system is also quite limited, primarily to the orange-red range. Therefore, some LEDs in a mixed system suffer from low-efficiency.

Second, this approach requires a complex system architecture: the different LED colors require separate driver channels; they also have different temperature-dependencies and aging characteristics, which must be compensated for to maintain the desired chromaticity. This complexity increases system cost. As a result, at present the combined-LED approach is mainly used in niche applications where active chromaticity control is required.

2.2. Phosphor down-conversion

In this approach, light is emitted at short wavelengths by a "pump" LED. Some of this pump light is absorbed by phosphor particles surrounding the LED, and down-converted to longer wavelengths. Most commonly, the pump LED is blue and is combined with a green/yellow and a red phosphor to form white light, as shown in Fig. 1(b). The concentration of these phosphors controls how much pump light is converted and how much is transmitted, in order to obtain a desired SPD.

From an efficiency standpoint, this approach is preferred today because good phosphors have high quantum yields (the ratio of emitted photons to absorbed photons), surpassing 90%. This is also a relatively simple technology, whose main