Energy efficiency and color quality limits in artificial light sources emulating natural illumination

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Abstract: We present in this work a calculation of the theoretical limits attainable for natural light emulation with regard to the joint optimization of the Luminous Efficacy of Radiation and color fidelity by using multiple reflectance spectra datasets, along with an implementation of a physical device that approaches these limits. A reduced visible spectrum of blackbody radiators is introduced and demonstrated which allows lamps designed to emulate natural light to operate with excellent color fidelity and higher efficiency as compared to full visible spectrum sources. It is shown that even though 3,000K and 5,500K blackbody sources have maximum efficacies of 21 lm/W and 89 lm/W, respectively, reduced-spectrum artificial light sources can exceed those values up to 363 lm/W and 313 lm/W, respectively, while retaining excellent color fidelity. Experimental demonstration approaching these values is accomplished through the design and implementation of a 12-channel light engine which emits arbitrarily-tunable spectra. The color fidelity of the designed spectra is assessed through Color Rendering Maps, showing that color fidelity is preserved uniformly over a large spectral reflectance dataset, unlike other approaches to generate white light.

OCIS codes: (330.1710) Color, measurement; (330.1715) Color, rendering and metamerism; (330.1730) Colorimetry; (230.3670) Light-emitting diodes.

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1. Introduction

Energy efficiency is one of the major concerns of modern lighting technologies [1]. Light Emitting Diodes (LEDs) have demonstrated to offer excellent energy savings while at the same time providing white light with good color fidelity to sunlight [2–4]. However, there is still a lack of consensus on how to define an index for color quality [3, 5–7], which has been the objective of the CIE Technical Committee (TC) 1-69: "Color Rendition by White Light Sources". This TC came to an end in 2014 with no agreement on the right metric suitable for industrial use. It became clear that there were two distinct tendencies that divided the committee, one advocating a color fidelity scheme (giving rise to the new TC 1-90: "Color Fidelity Index") while the other defended a color metric based on user preference (resulting in TC 1-91: "New

Methods for Evaluating the Color Quality of White-Light Sources"). While TC 1-90 is working with improved versions of the Color Rendering Index (CRI) [8] and with the Metamerism Index [9], TC 1-91 uses subjective indexes that require psycho-physical experimentation, such as the Color Quality Scale (CQS) [5, 6], the Memory Color Rendering Index (MCRI) [10], the Feeling of Contrast Index (FCI) [11] or the Categorical Color Rendering Index (CCRI) [12], among others.

In recent years, LED light engines based on arrays of single-peak LEDs are raising much interest [13, 14]. Their integrated electronics make it possible to change the intensity of each channel so that the emitted spectrum can be fully controlled. When these light engines are composed of a sufficient number of wavelength channels, it is possible to engineer the right spectral content that fulfills certain constraints and to find tradeoffs between color quality and energy efficiency metrics. In particular, in this paper, we have implemented a methodology to find the energy efficiency and color quality limits that implicitly emerge when trying to emulate natural illumination. For this, throughout the text, we assume a color fidelity scheme, and will use indexes that are suitable for representing fidelity to sunlight, such as the CRI. Also, several different reflectance spectra databases are used in order to make our conclusions as general as possible. The idea is very simple: if blackbody spectra give a CRI of nearly 100, they can be used as an initial starting point. In subsequent iterations the blackbody spectrum can be cut by the edges (left and right edges, or λ_{left} and λ_{right}). This approach narrows the spectrum down towards 555 nm which is the maximum sensitivity of the eye for photopic vision [15], and thus improves the Luminous Efficacy of Radiation (LER) until finding the desired tradeoff between LER and CRI. Although there are several works in the literature trying to establish numerical limits and tradeoffs between LER and color fidelity [16, 17], none of them uses our approach of maximal spectral resemblance to a blackbody radiator. These works also use a reduced number of reflectance samples, which constraint the validity of their results to a very limited set of real life applications.

2. Reduced visible spectrum in lamps

To explore the effect of spectral reduction for a given CCT (Correlated Color Temperature), the efficacy, CRI, Δ_{uv} (deviation from blackbody locus), and final CCT have been computed for a set of 28,900 reduced visible (RV) spectra, corresponding to all the blackbody spectra that have been windowed, i.e. reduced (or multiplied by zero) in the short-wavelength range (left edge or λ_{left}) of 380-550 nm and/or reduced in the long-wavelength range (right edge or λ_{right}) of 560-730 nm, with a resolution of 1 nm. As seen in Fig. 1, all these resultant spectra can be depicted through a 2-D color-value scale as a function of the wavelength cut-offs (λ_{left} and λ_{right}). In the first two columns, for each CCT, the plots show the R_a (general CRI) and the LER (in lm/W.) It is seen that when [λ_{left},λ_{right}]=[400, 700] nm, the spectrum is indistinguishable from a FV (full visible) blackbody spectrum (i.e. CRI=100) while the LER is higher than that of a FV blackbody spectrum with the same color temperature. By contrast, when [λ_{left},λ_{right}]=[550, 560]nm, the spectrum is nearly a singular spike, centered at 555 nm, with LER close to the efficacy limit ($\sim$683 lm/W) but with total inability to render any color besides the 555 nm green. Other than these two extremes, all combinations result in intermediate values of R_a and LER. Since only a subset of those values is interesting, the following discusses reasonable limits on these data, by focusing on high color quality and high efficacy.

In order to find reasonable RV spectral ranges, a lower bound on CRI and LER, and an upper bound on Δ_{uv} is selected. These restrictions delineate two different regions in the R_a and LER plots, which may or may not intersect. The plots in the third column of Fig. 1 show the intersecting areas, depicted through a 2-D color-value scale, derived from a score function, S, given by

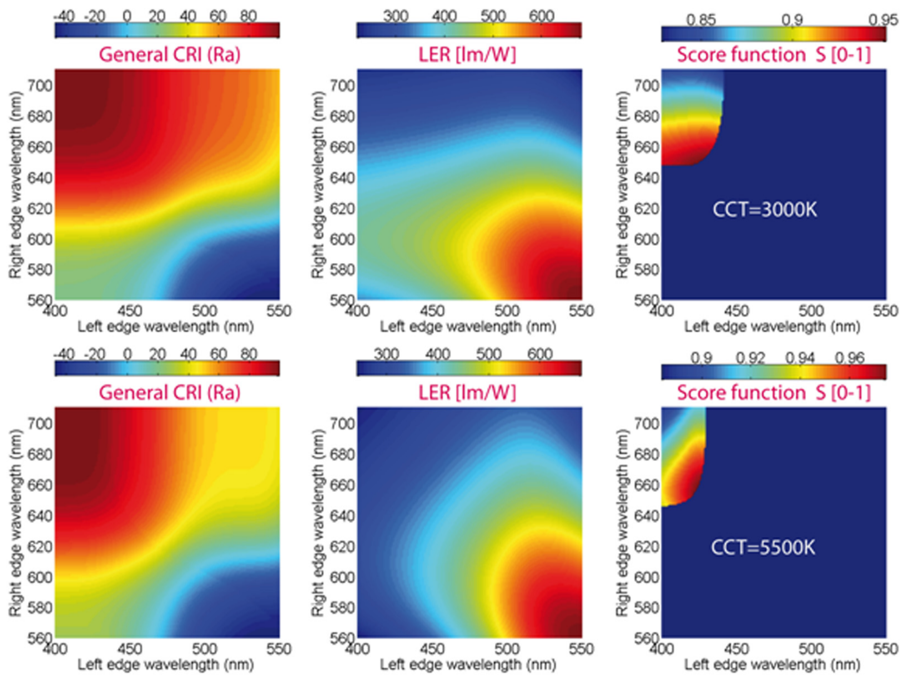

Fig. 1. Spectral limits for natural-light emulation. Trade-offs between R_a (left column) and efficacy (central column) in Reduced Visible blackbody spectrum light sources with 3,000K and 5,500K CCTs. The right column gives the score, S, obtained using Equation (1) when a spectrum satisfies the (user-defined) criteria of $R_a > 90$, Efficacy>200 lm/W and $\Delta_{uv} < 0.0054$

$$S = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{R_a}{R_a^*}\right)^2 + \left(\frac{Eff}{Eff^*}\right)^2} \tag{1}$$

where R_a^*=100 and Eff^* is the maximal LER for a particular target CCT which satisfies the upper-bound restriction on Δ_{uv}. For this example, we have restricted the output of our algorithms to show results that satisfy $\Delta_{uv} < 0.0054$. The region of intersection is notably reduced when such a low value for Δ_{uv} is imposed. However, this is a reasonable limit to set in order to assure that the resulting color coordinates of the light spectrum occur close enough to the blackbody locus such that the source can be considered a “true white” which emulates natural light.

3. Limits in emulating natural light

Unlike in previous attempts found in the literature [18–21], our method uses continuous blackbody radiators for mimicking natural light through a combination of narrowband emitters to get optimized values for the LER and R_a. These mimicked blackbody spectra, although being narrowed down by the edges, can be still be considered as being broadband (there are no regions without radiant power or deep gaps) since the power distribution spans almost the whole visible region, avoiding the deficiencies that the CRI shows when dealing with narrowband spectra [6] and the utilization of CRI as a quality (in this case fidelity) indicator is well justified. It is useful

#214288 - $15.00 USD Received 25 Jun 2014; revised 25 Aug 2014; accepted 6 Oct 2014; published 23 Oct 2014

to analyze the results from the third column in Fig. 1, where the "natural" conditions $R_a \geq 90$ and $\Delta_{uv} < 0.0054$ and desired efficacy LER ≥ 200 lm/W are imposed. For a specific CCT, two different scenarios can be drawn depending upon whether the optimal parameter is chosen to be LER or R_a.

Figure 2(a) shows that the theoretical limits for LER of the most natural source attainable are [363, 315] lm/W for CCTs of [3,000K , 5,500K], always preserving $R_a \geq 90$. The criteria of acceptability can, of course, be set higher or lower. For example, in applications demanding superior color quality and the highest resemblance to natural illumination, Figure 2(b) shows that the LER reduces to [250, 262] lm/W for CCTs of [3,000K , 5,500K], but (in this case) preserving a R_a above 99.

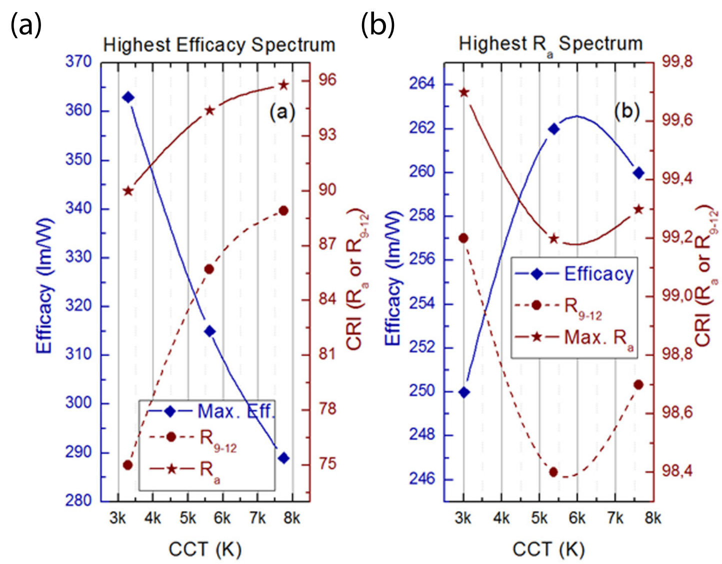

Fig. 2. Limits to photometric properties of natural light. Theoretical maximum achievable efficacy and color-rendering limits for two different scenarios: (a) optimized for highest efficacy and (b) optimized for best color quality, emulating natural light. (Solid and dashed lines are spline interpolations of data, and should be understood as a simple guide to the eye)

Further study of this method of optimizing spectra results in details as provided in Table 1. Considering the best rated spectra, it is seen that by narrowing the visible range down to [424–649, 424–658] nm, the efficacy can be increased from [21, 89] lm/W in a full-spectrum blackbody radiator, up to [363, 313] lm/W for a reduced visible spectrum blackbody radiator, for projected CCTs of [3,000K , 5,500K], always preserving R_a above 90. This clearly indicates that efficacy in a light source can be excellent, and simultaneously high color quality can be retained, if the spectral content of the lighting device is properly controlled.

The results for the best [3,000K , 5,500K] RV spectrum, shown in Table 1, demonstrate that as little as ~60% of the visible spectrum is sufficient to maintain LERs as high as [363, 313] lm/W while, at the same time, preserving outstanding light quality within the visible range, as demonstrated by the Color Rendering Maps (CRMs) [22] in Fig. 3. We refer to these values as being reasonable candidates to represent the theoretical maximum LER limits achievable by any lighting technology designed to emulate natural illumination.

In order to further evaluate color fidelity, a set of test reflectance spectra of a sufficiently wide

#214288 - $15.00 USD Received 25 Jun 2014; revised 25 Aug 2014; accepted 6 Oct 2014; published 23 Oct 2014

Table 1. Spectral parameters of best natural–light emulation. Detailed information of Highest Efficacy (HE), Highest R_a (HR$_a$) and Highest Score (HS) spectra

Highest Efficacy (HE)	**Highest Ra (HRa)**	**Highest Score (HS)**
Emulation at **3,000K**. Target Efficacy = **364.41 lm/W**		
$E_{ff} = 363\, lm/W$ $Ra = 90.0$ $S = 0.950$ $\Delta_{uv} = 0.0053$ $\Delta\lambda = [421, 648]$ $CCT = 3,280K$ $R_{9-12} = 75.0$	$E_{ff} = 250\, lm/W$ $Ra = 99.7$ $S = 0.856$ $\Delta_{uv} = 0.0002$ $\Delta\lambda = [403, 703]$ $CCT = 3,010K$ $R_{9-12} = 99.2$	$E_{ff} = 363\, lm/W$ $Ra = 90.5$ $S = 0.951$ $\Delta_{uv} = 0.0054$ $\Delta\lambda = [424, 649]$ $CCT = 3,260K$ $R_{9-12} = 76.0$
Emulation at **5,500K**. Target Efficacy = **314.92 lm/W**		
$E_{ff} = 315\, lm/W$ $Ra = 94.4$ $S = 0.972$ $\Delta_{uv} = 0.0054$ $\Delta\lambda = [421, 653]$ $CCT = 5,620K$ $R_{9-12} = 85.7$	$E_{ff} = 262\, lm/W$ $Ra = 99.2$ $S = 0.916$ $\Delta_{uv} = 0.0021$ $\Delta\lambda = [421, 709]$ $CCT = 5,370K$ $R_{9-12} = 98.4$	$E_{ff} = 313\, lm/W$ $Ra = 95.4$ $S = 0.975$ $\Delta_{uv} = 0.0053$ $\Delta\lambda = [424, 658]$ $CCT = 5,490K$ $R_{9-12} = 88.6$

range of hue, chroma and lightness are required. Such set must contain all the colors present in the objects associated with the application of interest. With the purpose of widening the validity of our results, we use a number of different datasets [23]. A first dataset uses the full range of reflectance spectra used in the Munsell Book of Color [24, 25] used for color assessment in industrial applications. A second set evaluates color rendering using the Agfa IT8.7 standard, a common reference in color management for photographic reproduction processes. The third set includes a large number of reflectance spectra from the leaves of pine, birch and spruce trees. A fourth set uses the reflectance spectra of flowers and leaves of plants while a final set evaluates color rendering properties using a large number of artificially generated smooth reflectance spectra.

Other authors have demonstrated good color appearance modeling using 1000 reference colors [26], and reasonable improvement with as few as 17 reference colors [27]. The CRMs for the best rated (HS) spectra for each color temperature are shown in Fig. 3. Besides the two reduced blackbody spectra, a narrowband RGB LED spectrum (CCT=3,000K) and triphosphor fluorescent spectrum (CCT=5,500K) are shown as a comparison. Each row shows both 3,000K and 5,500K best rated (HS) spectra, the RGB and finally the fluorescent illuminant evaluated over a different set of reflectance spectra. While the superior color fidelity of the reduced blackbody spectra is clearly seen, certain deficiencies show up depending on the particular set of reflectance spectra. Since Eq. (1) only involves R_a for the evaluation of color quality for a given spectrum, the best rated ones poorly reproduce some saturated colors such as the color represented by R_9 (saturated red). This deficiency diminishes with increasing CCTs, but at the

#214288 - $15.00 USD Received 25 Jun 2014; revised 25 Aug 2014; accepted 6 Oct 2014; published 23 Oct 2014
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expense of a reduction in the energy efficiency. These detected color reproduction anomalies essentially found in the saturated red and blue regions of the a^*,b^* chromaticity diagram and especially visible in Fig. 3(e) are due to the spectral cut-offs in the tails of the visible spectrum, and reinforce the validity and importance of the visual CRM index. In addition, despite the tight control held over Δ_{uv}, spectral reduction brings about a side effect to a fundamental characteristic of the resulting artificial light, i.e. a slight shift in the CCT. However, in the worst case there is less than 9% difference between the projected and the final CCT of the reduced visible spectrum.

4. Implementation of a light engine approaching the theoretical limits

Beyond the theoretical approach developed up in sections 3 and 4, to demonstrate that the predicted results can be realized using currently-available technologies, a tunable source, capable of generating arbitrary spectra was built. The light engine uses an array of monochromatic LEDs covering peak wavelengths in the 425–670 nm range. Each wavelength channel is composed of a different number of LEDs emitting at the same wavelength, with a total of 12 channels and 24 LEDs. Because the individual LEDs use different semiconductor materials from those in adjacent channels, and have significantly–differing current–voltage characteristics, each channel requires a unique constant current driver. To emulate an arbitrary spectrum, a Matlab–based fitting program is used to select the necessary intensities of the individual channels (based on reference measurements of each diode), minimizing the root–mean–square error between the superposed diode outputs and the desired total target spectrum. The resulting calculated intensity for each channel dictates the corresponding pulse width modulation of the constant–current driver for that channel. The superposition of all channel intensities closely matches the target spectrum. A highly conductive thermal path from the LED package to the heat sink ensures optimal thermal stability. Thermal dependency of the emitted spectra is further minimized by a closed loop thermal feedback system monitoring the temperature of the LEDs. The result is a compact, yet powerful light engine capable of emulating arbitrary illumination spectra. Prior to the experimental measurements, the LED assembly was thermally and spectrally characterized in an integrating sphere.

Figure 4 shows the measured spectral power distribution of the light engine for each reduced blackbody input spectrum (red dotted line), based on input from the best-rated (HS) spectra for CCTs of 3,000K and 5,500K (Table 1). Table 2 shows the corresponding LER, CRI, Δ_{uv}, CCT, R_9 and R_{9-12} for the measured and theoretical (optimized) spectra. The measured output performance indicators reasonably match the expected ideal, as seen in Table 2. R_9 and R_{9-12} are included here since they represent the ability to render saturated colors and are frequently poorly reproduced by conventional LED approaches.

Although other implementations of tunable sources can be found in previous works [28], the motivation underlying these developments is either metrology or psychometric experimentation in large rooms or spaces, involving complicated and expensive designs not suitable for commercial purposes. Our light engine demonstrates a simple approach to a compact multichannel LED solution, with no other complication beyond that of a typical LED based design (being needed to account for thermal management, optical design, color shift compensation, etc.), at a price not much higher than that of a currently available high–end luminaire. Natural spectra such as sunlight, are difficult to reproduce using available energy-efficient lighting technologies. Beyond the personal appeal of natural appearance in general lighting, there are important applications where emulation of natural light can be critical. The medical sector needs very high color rendering, but without ultraviolet or infrared content (i.e. surgical applications). Certain health and safety constraints, especially concerning ocular and neuroendocrine issues, need to be met [29]. Museums need very specific, standardized light sources for safely, yet vividly,

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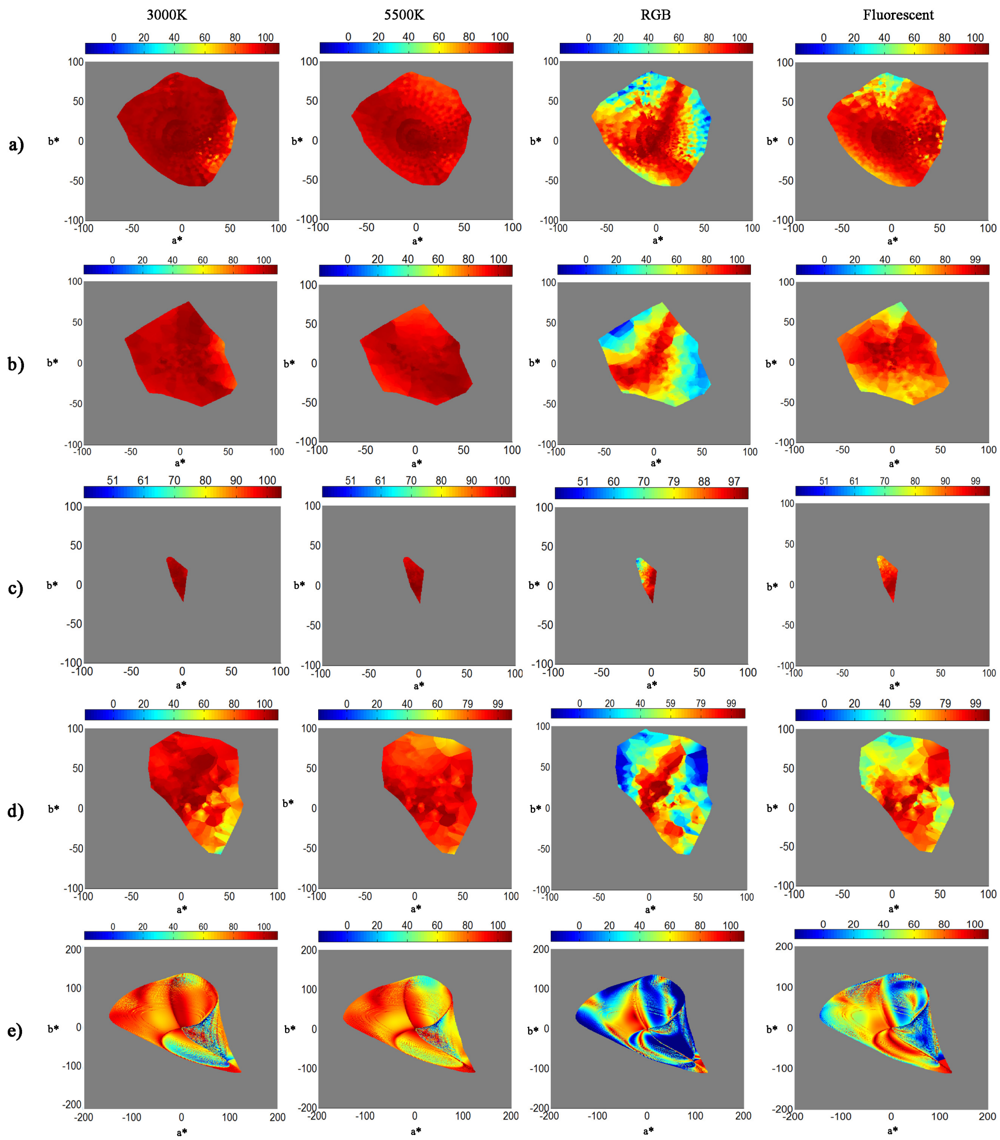

Fig. 3. Color Rendering Maps (CRM) represented in the CIE 1976 (a*, b*) color space for the best rated (HS) reduced visible spectra with a CCT of 3,000K and 5,500K, an RGB LED based light source with a CCT of 3,000K and finally a triphosphor fluorescent light source with a CCT of 5,500K. Row (a) shows the color fidelity of the light sources tested using 1,269 reflectance spectra of the Munsell Book of Colors. Row (b) uses the Agfa IT8.7 standard while rows (c) and (d) show the color rendering properties evaluated over a large number of reflectance spectra of natural materials such as different woods and leaves (c) and flower leaves (d). CRM (e) uses a comprehensive dataset using thousands of artificially generated smooth reflectance spectra, including reflectance data not occurring in existing man-made or natural materials

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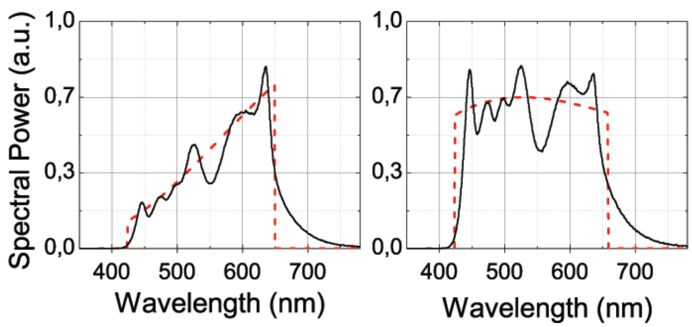

Fig. 4. Measured light engine spectral power distribution (solid line) compared with ideal reduced- spectrum input (dotted line) for 3,000K and 5,500K

illuminating collections [30, 31]. Hybrid lighting, combining daylight with artificial sources in order to provide uniform illumination over an arbitrary period of time [32], can benefit significantly. There are also specialized needs in graphic arts, lighting design, photography and cinematography. Spectrally–tunable light sources, such as the light engine shown here, although more complex than current energy–efficient lamps, allow the theoretical limits of natural light emulation to be reached up to any desired extent, accommodating the trade–offs between color quality and energy efficiency.

Table 2. Efficacy and color quality assessment of the real light engine spectra shown in Figure 4 compared to the best-rated spectra obtained from the calculated theoretical limits

Parameter assessment	**3,000K**	**5,500K**
LER (theoretical, lm/W)	363	313
LER (engine, lm/W)	329	295
$\mathbf{R}_a$ (theoretical)	90.5	95.4
$\mathbf{R}_a$ (engine)	94	92.1
Δ_{uv} (theoretical)	0.0054	0.0053
Δ_{uv} (engine)	0.0054	0.0053
CCT (theoretical, K)	3,260	5,490
CCT (engine, K)	3,256	5,494
$\mathbf{R}_9$ (theoretical)	39.1	66.3
$\mathbf{R}_9$ (engine)	62.5	88.2
$\mathbf{R}_{9-12}$ (theoretical)	76.0	88.6
$\mathbf{R}_{9-12}$ (engine)	85.2	87.1

5. Conclusions

The method of maximizing the LER while maintaining maximal natural appearance of light can be accomplished using a RV spectrum. At any given CCT, there is a maximum LER value which exhibits optimal and full-gamut color fidelity as assessed by the CRMs. Even with such a judicious choice, there exist maximal LER values in any lighting device which is intended to

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emulate natural light. The results shown here indicate, however, that intelligent light engines can be designed with high color fidelity and a luminous efficacy of radiation which far exceeds values associated with current lighting technologies.

Theoretical calculations show that emulation of natural light is possible through a RV blackbody spectrum, showing LER values up to 363 lm/W and 313 lm/W, and R_a values of 90.5 and 95.4, for 3,000K and 5,000K, respectively. Experimental demonstration approaching these values is accomplished through the design and implementation of a 12-channel light engine which emits arbitrarily–tunable spectra, showing LER values up to 329 lm/W and 295 lm/W, and R_a values of 94.0 and 92.1, for 3,000K and 5,000K, respectively. It is also shown that saturated colors are rendered well ($R_{9-12} > 85$). Finally, the natural resemblance of the designed spectra is further assessed through Color Rendering Maps, showing that color fidelity is preserved uniformly over a large spectral reflectance dataset, unlike other approaches to generate white light consisting of either phosphor-converted LEDs or a limited number of monochromatic channels [13, 14].

Acknowledgments

The research was partially supported by the European Regional Development Funds (ERDF, “FEDER Programa Competitivitat de Catalunya 2007-2013”). JC acknowledges support from the SILENCE[2] (TEC2010-17472) from the Spanish Ministry of Science and Innovation (MICINN). The research was also partially supported by the European Commission, under the FP7 project HI-LED (Contract No. 619912).