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Hybrid Solid-State Lighting Design

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The transition from incandescent lighting to more energy-efficient options is projected as a major opportunity for solid-state lighting (SSL.) The current prevailing technology for white-light SSL uses a nitride semiconductor blue LED combined with a down-converting YAG:Ce yellow phosphor. The residential use of LED lights presents challenges beyond efficiency, because of very-high color-rendering requirements, and the practical aspects of the current costs of LED lamps. Finding the balance between energy efficiency, color quality, and price, such that the resulting light source is appealing to the majority of consumers, is the major obstacle to SSL acceptance in the residential sector. We show here a potential approach for balancing efficiency, color quality, and costs by using a hybrid LED source, where the light engine uses down-conversion combined with monochromatic LEDs. The results are obtained starting with simulations of calibrated sources, and then verified experimentally using the tunable Light Engine in our laboratories.

The photometric efficiency of visible LEDs, both for pump-phosphor down-conversion devices as well as for monochromatic semiconductors, is a strong function of the emissive power in a given device. An ordinary warm-white high-power phosphor converted InGaN device operated at 50mW will show an efficacy of almost 200lm/W. However, the same device, operated at 2.25W will have only 45lm/W efficacy. In an ordinary residential application, such as R-30 downlight replacement, the source needs a 600 lm flux. The semiconductor costs alone constrain that the LEDs must be operated in their highest-power, yet lowest-efficacy mode. Even at that, this requires 6 LEDs in each lamp. To achieve this flux and keep the lamp affordable is accomplished by paying a price in color quality. Obtaining a CRI over 80 in this case is problematic, and if R9 (saturated red) is included, the metric is even lower. The color can be improved by adding an additional red phosphor; but at a further price of lost efficacy, since the blue LED is now down-converting two phosphors in parallel, and the red phosphor is typically less efficient, and less thermally stable, than the yellow phosphor. A proposed solution has been to use four monochromatic LEDs, without any down-conversion. This improves the efficacy substantially[1]; but the lack of a primary green LED peaking at 560nm (the part of the visible spectrum to which the eye is most sensitive) further degrades the color rendering and the visual quality of the source.

We find that a hybrid SSL source, using one monochromatic LED in parallel with one channel of down-conversion (using a blue-pump with green phosphor) improves the color quality without sacrificing significant efficacy. This occurs because only the single down-converted green channel is operating in a less-efficient mode. The higher overall efficacy allows for a lower cost in the total number of required semiconductors. Figure 1 shows the spectra of three sources with a CCT of 3000K: a blue LED-YAG:Ce standard device, a four color monochromatic source and a single monochromatic red LED plus down-converted green hybrid source. Table 1 shows the respective performance metrics of these three approaches.

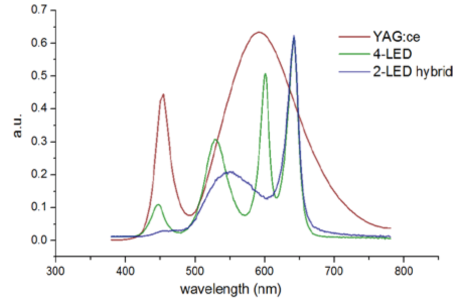

Figure 1: Spectral measurements

	YAG:Ce	4-LED	2-LED hybrid
LER (lm/W)	316	348	345
Luminous Efficacy (lm/W)	45	54	55
CCT (K)	2935	3027	3024
CRI	72	85	80
R9	-13	98	50

Table 1: Performance and characteristics

Several variables are considered in making the tradeoff between efficacy, color quality and cost. (1) The monochromatic LEDs are not equally efficient, equally reliable, nor equal in cost. Judicious selection of the specific channels wavelengths is critical. (2) The luminous flux, depending on the desired final spectrum, will not be the same for each channel, and therefore the LED/pump drivers for each channel differ. This can have significant cost and/or efficiency implications. (3) Because of the differing flux in each channel, the junction temperature in each semiconductor will also differ. This can have both performance and heat-dissipation implications which need to be considered. (4) Judicious selection of specific phosphors needs to take into account certain packaging requirements, especially if the materials are notably heat or moisture sensitive. (5) There are multiple combinations of semiconductors with down-conversion devices which can achieve this result; but consideration needs to be made of the degradation lifetime of the specific phosphor used in the down-conversion channel. This channel will have a significantly shorter lifetime than the monochromatic semiconductors, and will also be the determining factor[2] in the lifetime of the source overall.

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