

# Photometric design of color-conversion LEDs

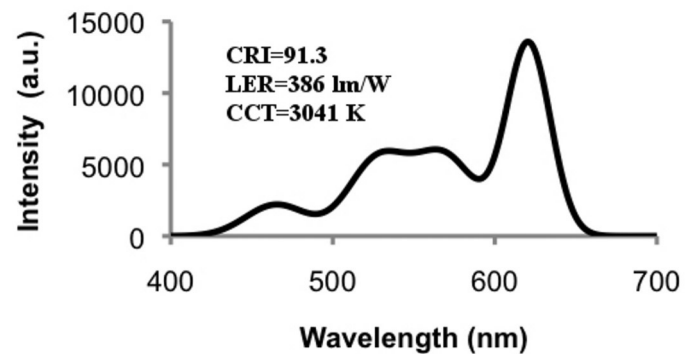
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*Selected combinations of narrow-emitter nanophosphors, made of colloidal quantum-dots, are integrated into LEDs to achieve photometrically efficient white light sources.*

Traditional broad-emitter phosphors are made by incorporating a combination of rare earth ions into ceramic powders. Although these types of phosphors are good for photon conversion across a broad spectrum, fundamental problems related to their photometric performance still persist. In particular, there are issues associated with a set of broad and continuous emissions that happen at long wavelengths. These emissions are usually accompanied by a tail, and they are scattered by the formation of large aggregates. Photometric performance issues such as these highlight the need for alternatives to traditional phosphors, and a suitable option seems to be the so-called luminophors.

In our work, we show that selected combinations of narrow-emitter nanophosphors, made of colloidal quantum-dots, can be integrated into LEDs to achieve high-quality white light. In order to demonstrate the photometric efficiency of these devices, we used numerical simulations and experimental proof-of-concept demonstrations. Our work suggests that high efficiencies can be achieved by using collective narrow emitters that allow for the tuning of the white light spectrum rather than continuous emitters.

The quality of white light can be evaluated using several photometric figures-of-merit. One of them is the color rendering index (CRI), which measures how efficiently a white light source reflects the real colors of an illuminated object. A good white light source possesses a CRI of 90 or above. An additional quality criterion is the luminous efficacy of optical radiation (LER), which represents the efficiency of the generated white spectrum in terms of the perception of the human eye. LER values rarely go above 300lm/W<sub>opt</sub>. The correlated color temperature (CCT) is another figure-of-merit used for quality evaluation. It indicates the temperature of a Planck black-body radiator whose perceived color most closely resembles that of the light-source.



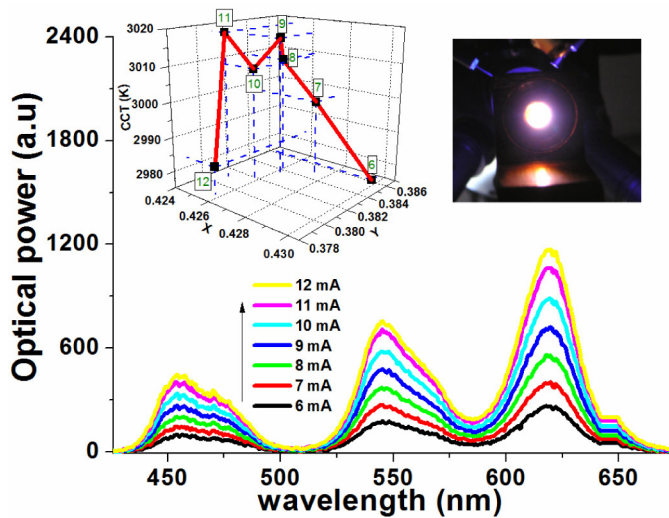
**Figure 1.** Spectrum generated using quantum-dot nanophosphors. The figures-of-merit CRI, LER, and CCT indicate the resulting photometric performance.<sup>2</sup>

Warm white light has CCT values smaller than 3500K, which makes it highly desirable for indoor lighting applications. All of these performance criteria cannot be simultaneously satisfied using conventional broad-emitter phosphors. For instance, traditional phosphors can achieve high CRIs, but not in conjunction with high LERs.

To date, LER values of 274lm/W<sub>opt</sub> are among the best reported performances of phosphor-based white LEDs.<sup>1</sup> This is partially because phosphors do not have the ability to tune different shades of white while simultaneously achieving high photometric performances. White LEDs integrated with quantum-dot nanophosphors have the necessary spectral purity to enable their white-light spectrum to be tuned. However, the complex relationship between the photometric figures-of-merit makes it difficult to achieve large values of CRI and LER together with low values of CCT. This requires spectral design and the optimization of the nanophosphor quantum-dots.

Of all the colors forming white light, red is the most critical for determining photometric performance.<sup>2</sup> Figure 1 shows a white-light spectra generated using a quantum-dot-based LED, with the resulting set of photometric figures-of-merit in the inset. Our results indicate that it is possible to obtain

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**Figure 2.** Electroluminescence spectra of the first quantum-dot-based white LED. This device integrates green, yellow, and orange-emitting quantum-dots—made of an inner core of cadmium selenide (CdSe) and an outer shell of zinc sulfide (ZnS)—into blue LEDs made of layers of indium gallium nitride (InGaN) and gallium nitride (GaN). The plots show the collective emission and chromaticity properties for different current injection levels at room temperature. Left inset indicates different operating points in the chromaticity diagram, with the values inside the squares representing the current injection levels in mA. Each point has a CCT value, which is indicated in the z-axis coordinate. Right inset shows a quantum-dot-based LED generating white light.<sup>3</sup>

high-quality, spectrally efficient white light by using quantum-dot nanophosphors.<sup>2</sup>

In previous works, we presented experimental demonstrations of spectrally efficient, high-quality white LEDs.<sup>3,4</sup> For these proof-of-concept demonstrations, we integrated red and green quantum dots—made of an inner core of cadmium selenide (CdSe) and an outer shell of zinc sulfide (ZnS)—into blue LEDs made of layers of indium gallium nitride (InGaN) and gallium nitride (GaN). This combination gave us white LEDs with CRIs larger than 80, LERs larger than  $300\text{lm}/W_{\text{opt}}$ , and CCTs smaller than 3250K.<sup>4</sup> By including an extra quantum-dot that emits in a different color, we achieved a four-color mixture that has a superior photometric performance (see Figure 2).<sup>3</sup> In Figure 2, point 12 has coordinates  $(x,y)=(0.425, 0.378)$  in the chromaticity diagram, a CCT value of 2982K, a LER of  $357\text{lm}/W_{\text{opt}}$ , and a CRI equal to 89.2. To the best of our knowledge, this LED has the highest reported photometric performance, which demonstrates that narrow-emitter nanophosphors can exceed the photometric performance of the best reported phosphors.

We have shown that specifically designed quantum-dot nanophosphors can be integrated into LEDs. These devices produce high-quality white light whose photometric efficiency is verified using experimental proof-of-concept demonstrations. The high photometric capabilities, large quantum yields and well-established synthesis methodologies of these nanophosphors make them a suitable alternative to conventional phosphors. The challenge now is to make environmentally friendly (e.g. cadmium-free) quantum-dot nanophosphors with comparable quantum yields.

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Hilmi Volkan Demir received his BSc from Bilkent University in 1998, and his PhD from Stanford University in 2004. He has contributed to the commercialization and licensing of several new technologies and startups in Turkey and France, which have led to more than 15 patent applications. He is the author of more than 70 publications in indexed peer-reviewed journals, and he has given more than 100 invited seminars. He is the recipient of national and international awards including the European Science Foundation European Young Investigator Award (ESF-EURYI) and the Turkish Scientific and Technological Research Council Young Scientist Award (TUBITAK-TESEVİK). He is a Fellow of Singapore's National Research Foundation. His research interests include high-quality white LEDs and innovative light-generation and harvesting.

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Talha Erdem received his BSc in 2009 from Bilkent University, where he is currently studying for a MSc. His research is focused on the design and implementation of high-quality, quantum-dot-integrated, white LEDs.

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From 1986 until 1994, Xiao Wei Sun studied for his BEng, MEng and PhD in photonics in Tianjin University, China. From 1994 to 1998, he pursued a second PhD in electrical engineering at the Hong Kong University of Science and Technology, Hong Kong. He is a SPIE and IoP Fellow and the recipient of the Nanyang Award for Research and Innovation 2009. He has co-authored over 250 publications in peer-reviewed journals.

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