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Color Science and Photometry for Lighting with LEDs and Semiconductor Nanocrystals

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Nanoscience and Nanotechnology

Nanoscience and nanotechnology offer means to assemble and study superstructures, composed of nanocomponents such as nanocrystals and biomolecules, exhibiting interesting unique properties. Also, nanoscience and nanotechnology enable ways to make and explore design-based artificial structures that do not exist in nature such as metamaterials and metasurfaces. Furthermore, nanoscience and nanotechnology allow us to make and understand tightly confined quasi-zero-dimensional to two-dimensional quantum structures such as nanoplatelets and graphene with unique electronic structures. For example, today by using a biomolecular linker, one can assemble crystalline nanoparticles and nanowires into complex surfaces or composite structures with new electronic and optical properties. The unique properties of these superstructures result from the chemical composition and physical arrangement of such nanocomponents (e.g., semiconductor nanocrystals, metal nanoparticles, and biomolecules). Interactions between these elements (donor and acceptor) may further enhance such properties of the resulting hybrid superstructures. One of the important mechanisms is excitonics (enabled through energy transfer of exciton-exciton coupling) and another one is plasmonics (enabled by plasmon-exciton coupling). Also, in such nanoengineered structures, the light-material interactions at the nanoscale can be modified and enhanced, giving rise to nanophotonic effects.

These emerging topics of energy transfer, plasmonics, metastructuring and the like have now reached a level of wide-scale use and popularity that they are no longer the topics of a specialist, but now span the interests of all "end-users" of the new findings in these topics including those parties in biology, medicine, materials science and engineerings. Many technical books and reports have been published on individual topics in the specialized fields, and the existing literature have been typically written in a specialized manner for those in the field of interest (e.g., for only the physicists, only the chemists, etc.). However, currently there is no brief series available, which covers these topics in a way uniting all fields of interest including physics, chemistry, material science, biology, medicine, engineering, and the others.

The proposed new series in "Nanoscience and Nanotechnology" uniquely supports this cross-sectional platform spanning all of these fields. The proposed briefs series is intended to target a diverse readership and to serve as an important reference for both the specialized and general audience. This is not possible to achieve under the series of an engineering field (for example, electrical engineering) or under the series of a technical field (for example, physics and applied physics), which would have been very intimidating for biologists, medical doctors, materials scientists, etc.

The Briefs in NANOSCIENCE AND NANOTECHNOLOGY thus offers a great potential by itself, which will be interesting both for the specialists and the non-specialists.

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Contents

Chapter 1
Introduction

Abstract Here we briefly emphasize the importance of lighting for our daily lives as well as its role in energy consumption. We very briefly introduce the problems that need to be addressed and finally summarize the contents of this brief.

Keywords Lighting · Energy consumption · LEDs

Light is an essential part of the human life and is considered an important trigger for the development of culture and knowledge. In modern times, light and together with it light-emitting devices including lamps, lasers, and displays have become an inseparable part of our lifestyle. Acknowledging this importance of light and underlying scientific breakthroughs, UNESCO announced 2015 as the "International Year of Light and Light-based Technologies" [1].

The significance of light shows itself in its share within the total energy consumption. Decreasing this amount is expected to substantially contribute to the efforts of mitigating the carbon footprint; therefore, there is a strong demand for developing efficient light sources [2]. Research addressing this need has already started to help reduce the share of the energy consumed by the lighting from ~20% in 2007 [3] to 15% in 2015 [4]. The driving force for this development has been the transition from the traditional light sources to the light-emitting diodes (LEDs) [5]. As tabulated by the US Department of Energy [6], an LED-based lamp consumes only ca. 20% of the energy that an incandescent lamp typically uses to deliver a similar brightness level. The US Department of Energy predicts that by 2030 the transition to LEDs will enable a total of ~40% energy saving. In addition to this saving, the bulb lifetime, which is 1000 h for incandescent lamps reaches, 25,000 h for the LED based lamps. This is also an important advantage of using LEDs to decrease the cost [6].

Two main strategies are followed to realize white-light emission using LEDs. The most straightforward approach is the collective use of multiple LED chips each individually emitting in different colors. However, despite being straightforward, this method of producing white light is significantly costly due to the driving electrical circuitry. In addition, different material systems required for such LEDs of varying color components further increases the production complexity and cost. More importantly, the efficiencies of the green and yellow LED chips are commonly low;

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therefore, the white LED luminaries using these LED chips suffer from low efficiencies. As a consequence, multi-chip approach for white light generation has not been able to find ubiquitous use. A more common method for this purpose relies on the hybridization of color converters with LED chips. In this method, a blue or near-ultraviolet (UV) LED excites the color converting material that is coated on top of the LED chip. Currently, the most common color converters are the phosphors made of rare-earth ions. These phosphors possessing near unity quantum efficiencies are typically very broad emitters spanning the spectral range from 500 to 700 nm. This spectral broadness allowing for white light generation is, however, their plague because the emission spectra of the phosphors extend toward the spectral region where the human eye is not sensitive anymore. It is also very difficult to fine-tune the spectrum of the LEDs using phosphors to increase the color quality by increasing the color rendering capability and shade of the white light [3, 7]. Another problem associated with these phosphors is the supply problems of the rare-earth elements threatening their future in optoelectronics [8]. At this point, narrow-band emitters such as colloidal nanocrystal quantum dots step forward as they enable spectral fine-tuning [9] while the saturated colors emitted by them allows for obtaining displays that can define colors as opposed to broad-emitters such as phosphors [10–12].

While designing light sources made of narrow-band emitters, one of the most important questions is how to achieve high quality and high efficiency. In this brief, we aim to establish guidelines to answer this question for indoor, outdoor, and display lighting applications. We start with the technical background on light stimulus and human eye, then continue with colorimetry and photometry. Next, we describe the guidelines for designing light sources made of narrow-band emitters in the order of indoor lighting, outdoor lighting, and display backlighting. Finally, we conclude this brief with a future perspective.

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