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Efficient Materials for High Quality Light Sources: Present Status and Future Prospects

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The mandate for transitioning to energy-efficient lighting poses conflicting challenges, particularly in developing sources which produce high-quality light for differing applications, while achieving the required efficiency. This also needs to be accomplished cost-effectively. In this presentation, several of these challenges are considered. The tradeoffs between color rendering and efficacy are demonstrated. Color rendering assessment metrics are examined, particularly in the context of on-going demonstration projects. The problems posed by current LED technologies are considered. New materials beyond nitrided semiconductors and phosphors are explored. Finally, the use of the Light Room for obtaining spectral quality data is demonstrated.

Intuitively, there is a tradeoff between color rendering and efficacy. A single monochromatic LED can be very efficient; but it renders only that single color. However, when luminescent materials are combined to emulate natural spectra, there are limits to the luminous efficacy of radiation (LER) which can be achieved[1] (Figure 1).

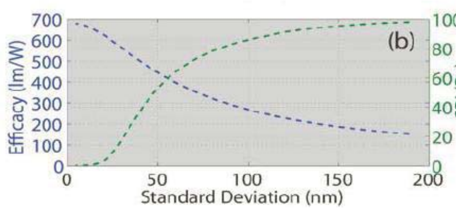

Figure 1: tradeoff between CRI and efficiency of a set of Gaussian spectra

In assessing color quality, there is agreement that the use of the General CRI (R_a) is becoming increasingly inaccurate. There is not, however, general agreement concerning which of several proposed metrics (including various objective and subjective schemes, considering both color fidelity and human preferences) is most suitable. We have developed the Color Rendering Map (CRM)[2] which gives either a 2-d or 3-d visual/graphical assessment metric instead of a numeric scale. This method leads to a more intuitive evaluation of color quality in differing applications. The application of the CRM will be demonstrated in the context of on-going demanding illumination projects, such as the EU LED4Art Project in the Sistine Chapel.

In achieving both efficacy and high color rendering, the use of LEDs and phosphors offers opportunities. At the same time, however, there are challenges. If monochromatic LEDs are exclusively used, there is a significant gap near 560nm where no practical, efficient LED technology exists. Consequently, the color rendering capabilities, using exclusively these sources, are limited. Using phosphors with LEDs ("down-conversion LEDs"), creates a further efficacy drop. The color rendering level of Plankian sources can be approached; but at a cost of an unaffordable drop in efficacy. SSL sources also suffer from operational problems ("droop"), heat dissipation issues, glare and optics design complexities.

There exist materials options beyond nitride-semiconductor LEDs and phosphors. Silicon SSL, using nanocrystals[3], offer an opportunity, using low-cost Si-based technology and sustainable materials, to formulate a broad spectrum which emulates a Plankian radiator. Luminescent quantum dots may open up the route to efficient, spectrally tunable and large-area light emitting devices. Also, the combination of luminescent clusters with optimized plasmonic particle shells has a two-fold advantage: First, the light extraction efficiency can be improved at selected wavelengths via photon-plasmon interactions, which enables a further degree of tunability, in addition to the one associated with particle/cluster size distributions. Second, radiative recombination rates of the luminescent materials can be significantly increased, which causes luminescence enhancement if the emission wavelength is close to the plasmon resonance wavelength.

Finally, there exists the challenge of evaluating a given novel light source in the context of its usage. We have developed a large "Light Room", which employs numerous 12-channel light engines. In this room, it is possible to emulate the appearance of virtually any visible-spectrum illumination scenario. Figure 2 shows the emulation of a demanding reduced-spectrum blackbody (3000K) using the light engines.

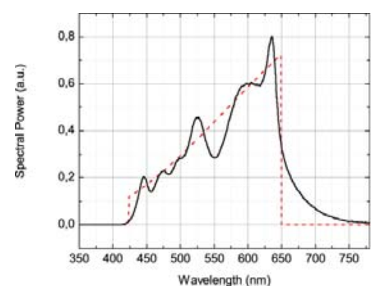

Figure 2. Reduced-spectrum blackbody (dashed line) synthesized using a light engine for color-quality analysis

In the Light Room environment, it is possible to demonstrate the appearance, as well as evaluate the applicability, of such a light source in use, without requiring actually making the light sources themselves. This is of significant benefit when designing sources for specialty environments, such as art museums, food displays, medical treatment facilities, etc..

The ultimate objective of the programs at IREC is incorporation of energy efficiency as one mitigation strategy in reducing carbon footprint and the effects of human-induced climate change. However, the usage of energy-efficient artificial light sources will remain problematic until the quality and properties of the new sources match the expectations.

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[1] J. Carreras, W. Hertog and C. E. Hunt, Efficacy and Color "Quality Limits in Artificial Light Sources Emulating Natural Illumination", *in submission* (2012)
[2] J. M. Quintero, A. Sudrià, C. E. Hunt and J. Carreras, "Color rendering map: a graphical metric for assessment of illumination", *Optics Express*, **20** pp. 4939-4956 (2012)
[3] Y. Berencén, J. Carreras, O. Jambois, J. M. Ramírez, J. A. Rodríguez, C. Domínguez, C. E. Hunt and B. Garrido, " Metal-Nitride-Oxide-Semiconductor Light Emitting Devices for General Lighting", *Optics Express*, 19(S3) pp. A234-244 (2011)