

The LED Lightbulb: Are we there yet?

Progress and Challenges for Solid State Illumination

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Abstract: Rapid improvement in light emitting diode (LED) performance and an annual multi-billion dollar lighting market is motivating worldwide development of LED based illumination systems. In addition to the traditional figures of merit of efficiency and high flux density, the white LED lamps must also have appropriate color characteristics. Current commercial white LED lamps have undesirable color temperatures and uniformity, and inferior color rendering. As discussed below, color uniformity in single phosphor lamps has been improved by deposition of thin uniform phosphor layers conformal to the LED die. Also, 2-phosphor LED lamps with white color characteristics typical of conventional incandescent and halogen sources are described. Furthermore, LED illumination offers additional features not practically achievable with conventional sources.

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1. Introduction

Rapid improvement in light emitting diode (LED) performance and an annual multi-billion dollar lighting market is motivating worldwide development of LED based illumination systems. Throughout the 90's, the luminous efficiency of monochromatic LED lamps improved to match and exceed conventional incandescent and halogen sources. More recently, development of large area "flip-chip" die, and improved package design have resulted in individual red, amber, green, and white LED lamps with flux exceeding 100 lumens, and blue LED lamps with greater than 1 W of optical power. In addition to energy savings, LED lifetime and robustness provides lower cost of ownership due to reduction or elimination of source replacement costs.

LED white emission is most efficiently generated by mixing light from red, green and blue LEDs. Although intrinsically efficient, this approach generally requires active feedback control. Mixing red, green and blue emission from phosphors pumped by UV LEDs is an alternate approach, but has reliability issues. Currently, most commercial white LEDs employ a hybrid of these methods, where by blue LED emission simultaneously pumps a phosphor, and mixes with the resulting amber phosphor emission.

In addition to the traditional figures of merit of efficiency and high flux density, the white LEDs must also have appropriate color characteristics. The color coordinates in the Commission Internationale d'Eclairage (CIE) chromaticity diagram of a light source is given by its spectrum. Sources with coordinates near the Planckian black body locus can be characterized by a correlated color temperature (CCT). The ability of a light source to make objects appear the same color as a black body source of the same color temperature is characterized by its color rendering index, Ra. Incandescent sources have Ra's near 100. Fluorescent sources can have Ra's from 70-90.

2. LEDs for general illumination

The color coordinates (as defined by the 1976 CIE specification) of single phosphor commercial high power white lamps are shown in Figure 1a. These lamps are characterized by CCT values near 5500K, and by Ra's below 80. The lack of a red intensity in the spectra of the single phosphor device can be observed in Fig 1b. The high CCTs and poor color rendering characteristics of these devices limit their illumination applications to primarily outdoor or portable lighting systems.

Improved color rendering and lower CCT can be obtained by the addition of a red phosphor. The spectra of one such lamp made with a mixed 2-phosphor system is shown in Fig. 1b. The color coordinates of several 2-phosphor lamps are indicated in Fig 1a. The range of color coordinate space spanned by these LED lamps includes 2800K typical for incandescent lamps, and 3100K characteristic of most tungsten halogen lamps. LED lamps with Ra values exceeding 90 have been obtained in both these regions. In addition to desirable color characteristics, the 2-phosphor LED lamps also have luminous efficiency comparable to or exceeding traditional incandescent and

tungsten-halogen general lighting sources. For example, the lamp corresponding to Fig. 1b has a luminous efficiency of 23lm/W.

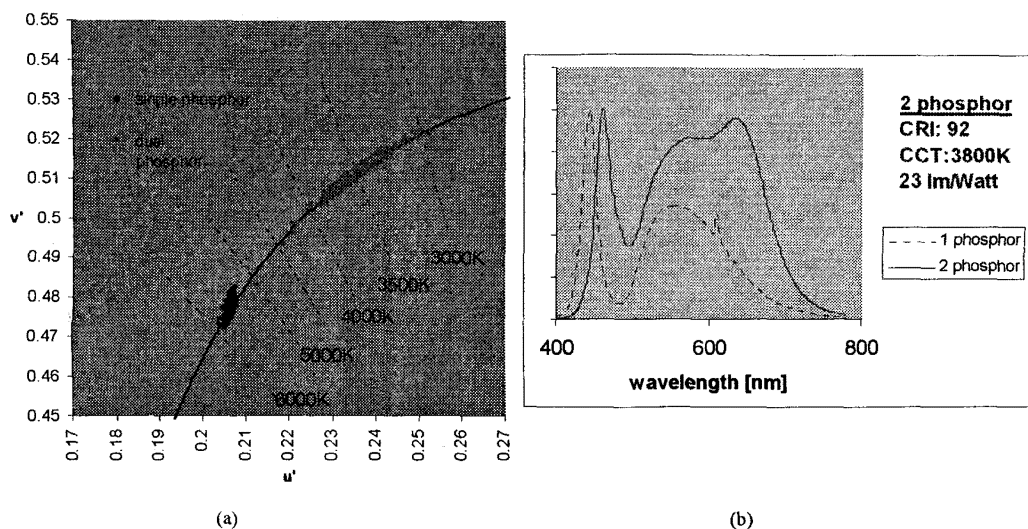


Fig. 1 (a) 1976 CIE chromaticity diagram indicating color coordinates and (b) example spectrum for single and dual phosphor LED lamps. The curve in (a) is the Planckian locus.

3. White Chips

Most white LED lamps commercially available are manufactured by embedding phosphor within the LED lamp package, typically in either the epoxy or other encapsulant surrounding the LED chip. More recently, a technique has been developed by which a conformal thin layer of a single phosphor is deposited around the die as shown in Figure 2a. The uniformity of this phosphor layer results in higher color uniformity of the LED lamp, compared to lamps made with the conventional method. A comparison of CCT as a function of viewing angle is shown in Fig. 3. The “hot spots” and lamp to lamp variation are both greatly reduced.

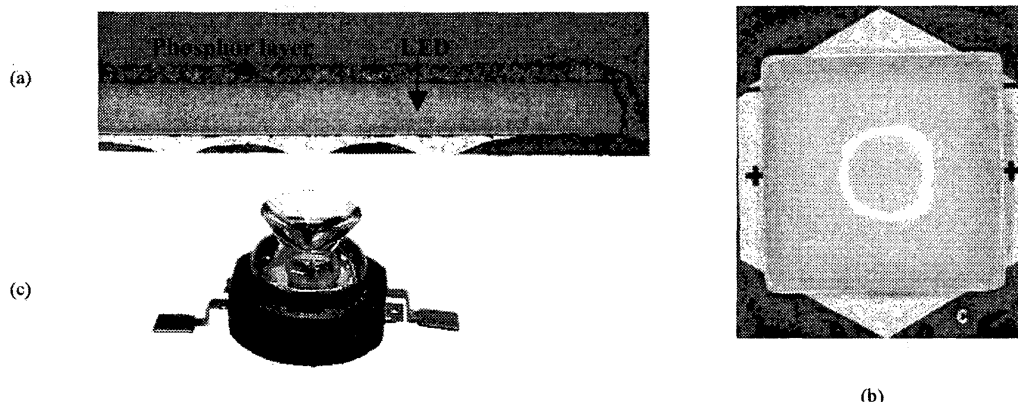


Fig 2. (a) Cross section of LED showing thin uniform phosphor layer conformal to LED die, (b) top view of white chip (center ring is artifact of illumination source) (c) side emitting LED lamp with white chip inside

In addition to improved color uniformity, the thin film coating is applied in such a way that results in a free standing LED “white chip”, as shown in Fig.2b. This chip has a smaller effective source size compared to traditional lamp sources, enabling more flexibility in secondary optic design and improved collection efficiency. Also, the elimination of a reflector cup (needed previously to contain the LED and phosphor slurry) enables alternate lamp

designs. Shown in Fig 2c, for example, is a side-emitting white lamp made with a white chip. Also, 5W (input power) lamps are made with 2mm x 2mm chips with a conformal phosphor coating. Lamp flux exceeding 150 lumens made from these large chip LEDs are routinely achieved. These represent the brightest LED lamps commercially available, with flux equivalent to a 15W incandescent bulb, in addition to having a 50 times longer lifetime and 3 times higher power efficiency.

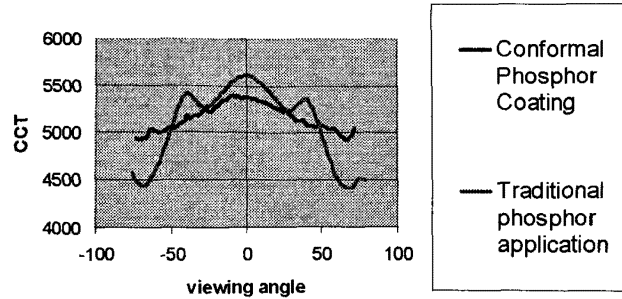


Fig. 3 CCT vs. viewing angle for LED lamp with conformal phosphor layer showing improvement in uniformity compared to traditional white LED.

4. Opportunities and Challenges

In addition to efficiency and lifetime benefits normally associated with LEDs, white LEDs now match the color characteristics of conventional illumination sources, as described above. Furthermore, LED based lighting systems can offer additional features not practically achievable with conventional sources. For example, as indicated in Fig. 2b, white LEDs with CCTs in the 3000-4000K range with good efficiency and excellent color rendering are readily achievable. In contrast, halogen sources are typically limited to CCTs of 3100K, beyond which lamp lifetime is dramatically reduced. Also, unlike conventional sources, lamps can be dimmed with minimal change in color characteristics.

Multi LED lighting systems offer unprecedented flexibility to create arbitrary light characteristics. The spectrum from a 31cm x 25cm demonstration "light box" designed to duplicate the CIE D65 illuminant spectrum between 420-650nm is shown in Fig 4, using blue, green, amber, red and white LED lamps. The CCT and CRI of the resulting emission is 6500K and 95 respectively, and has excellent spatial color uniformity ($du'v' < .005$). Also, in principle, with appropriate drivers, the color point and intensity of light can be tuned independently.

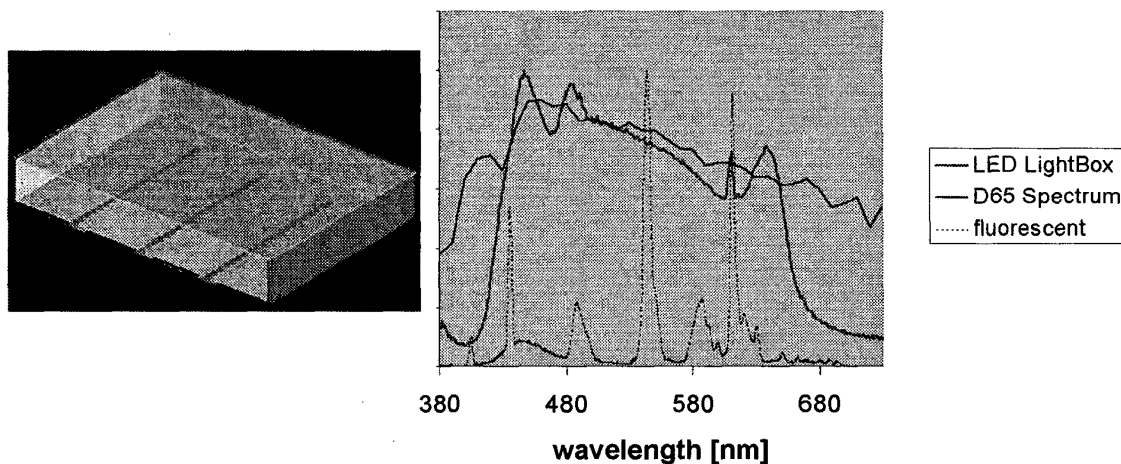


Fig 4. Diagram and spectrum of LED light box designed to match D65 spectra. Fluorescent spectrum is also shown for comparison.

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Finally, under specific conditions, LED's illumination systems can have high R9 through R14 values, which are not included in the conventional Ra definition. Shown in Table 1 are full color rendering indices for the D65 light box described, showing values above 90 for almost all indices. Color indices for the 2 phosphor system described above, and that for a tri-color fluorescent lamp are also given. Note that fluorescent sources are especially deficient in R9 (deep red)

Index	D65 Light Box	2 Phosphor Lamps Ra=93, CCT =3150K	tri-color fluorescent Ra=86, CCT=3100K
R ₁	95	92	99
R ₂	97	95	98
R ₃	97	95	61
R ₄	93	90	94
R ₅	96	91	90
R ₆	98	94	88
R ₇	95	95	91
R ₈	94	90	67
R ₉	85	75	2
R ₁₀	95	85	61
R ₁₁	94	88	80
R ₁₂	90	79	64
R ₁₃	95	92	94
R ₁₄	98	97	72

Table 1. Color Rendering indices for selected sources.

In order to displace conventional light sources, further increases in lumen/\$ are necessary. There is reason for optimism as there is still room for significant improvement in both semiconductor internal efficiency and lamp extraction efficiency. As such, we can look forward to the time when solid state lighting is as ubiquitous as today's lightbulb.