Research Assessment of Remote Phosphor Technology

Project: Light Cannon R&D

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Summary:

Remote phosphors have been used in a number of competing LED lighting products, and are known as one route to increase fixture efficiency. Removing the heat generating phosphor from the LED chip and allowing it to be independently dissipated through the lens or case assembly enables the LED junction to maintain a lower temperature for the same luminous output. Prototype films have been made in-house at Nemalux to assess coating of phosphor powders to generate custom emission spectra for individual projects or special applications.

Principles of Operation:

All single die white LEDs currently on the market make use of phosphors to achieve white light from the narrow band emitted from the semiconductor junction. While generally known as phosphors, the active materials in are actually fluorescent materials. As used in LED applications, incident light (typically Blue for white LED chips or fixtures) is absorbed by the phosphor layer, which then fluoresces, emitting light at a longer wavelength than the light initially absorbed. The combination of the longer wavelength light emitted from the phosphor and transmitted shorter wavelength light from the LED die combine to give a white appearance to the resulting spectra.

When a phosphor atom or molecule absorbs a photon from the LED die, an electron is excited from its ground state in the phosphor to a higher energy state. From this initial excited state the molecule loses energy (producing heat) as it passes through one or more intermediate states until it drops into the lowest vibrational level of the excited state. From this state the molecule undergoes a radiative transition back into the ground state, emitting a photon of a longer. The absorption to emission cycle typically takes 0.5 ns to 20 ns, and only once the process is complete can the same atom or molecule repeat the process.

The energy loss between the time that a photon is absorbed and when a photon is emitted is known as the Stokes shift. For example, if a phosphor absorbs a blue photon at 450 nm and emits a red photon at 650 nm the energy efficiency of the process is 69%, with 31% of the initial energy being converted to heat in the phosphor layer. The absolute efficiency of a phosphor system is equal to the multiplication of the quantum yield of the material (the ratio of emitted photons to absorbed photons) and the ratio of the emitted photon energy to the energy of the absorbed photon. Typical white-light remote phosphor conversion efficiencies are on the order of 180lm/Wrad (180 lumens out, given 1 Watt radiometric power of Royal Blue light incident on the remote phosphor layer – Source: Intematix ChromaLit documentation). As there is no relationship between the direction of the absorbed light and the emitted light, and incident light that is not absorbed has a high probability of being scattered, use of remote phosphors will always produce a wide angle emission profile.

Test Pieces:

Phosphor containing films were made by pouring the viscous phosphor-encapsulant slurry onto a flat panel with spacers placed around the edges, and then sandwiching another flat panel on top to spread out the mixture. In these prototypes a series of washers with a height of 0.8mm were used resulting in films that are approximately 0.9 mm thick. Once the slurry was sandwiched between the two plates, it was cured at 100°C for 1 hour. In early samples there were numerous air bubbles. With better de-gassing technique and a longer waiting period between slurry pour and cover placement films were made with few bubbles and very good uniformity. Using this method films can be made at least 14” by 14”, though if used for production, spray coating or subcontracting the coating to Intematix or other companies may be cost effective.

A spectrometer test test jig was constructed out of a cardboard box, with a cut-out at on end for the Ocean Optics spectrometer. Two interchangeable panels were made for the opposite end to fit the Royal Blue ACCANLED and Royal Blue XCANLED fixtures as test platforms (see Figure 1 for the test jig with XCANLED installed).

Figure 1: Spectrometer test jig. All corners sealed with opaque tape.

Intematix EY4453 Phosphor: White Emission (peak emission at 565nm)

Coatings were made with QSil 216 as an encapsulant. Two 0.9mm thick films were made at ratios of 1:2 and 1:4 phosphor to encapsulant (Figure 2, below). A Blue ACCANLED (463nm) was used for testing, and emission spectra taken using an Ocean Optics spectrometer. At a 1:2 loading the resulting light was very orange, clearly too high of a loading to produce a white output. The 1:4 loading was more promising, producing a warm-white emission spectrum. See Figure 3 (below) for the emission spectra of these two films.

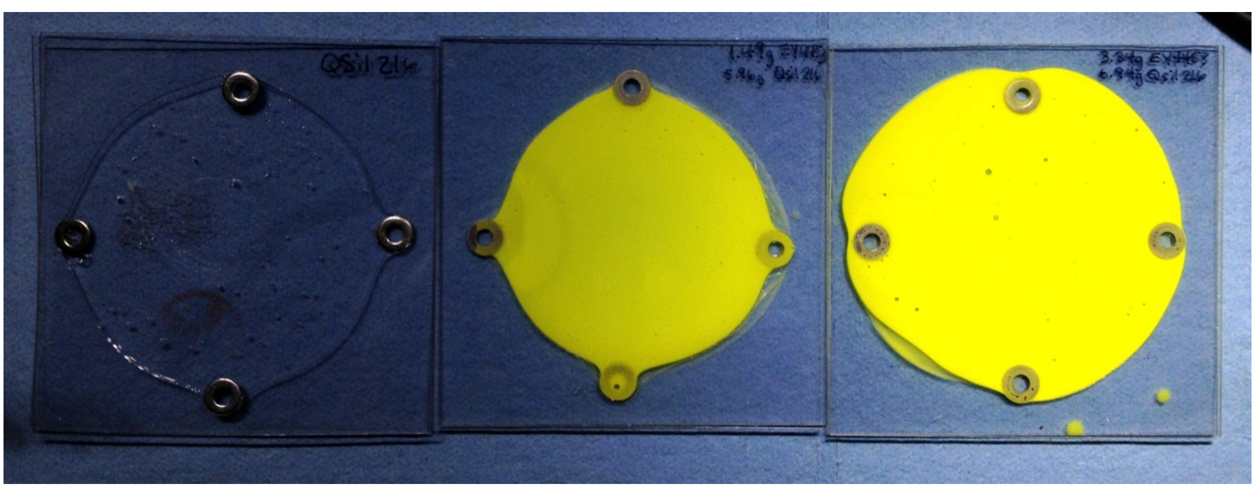

Figure 2: EY4453 White-emitting phosphor prototypes: (Left) Highly transparent QSil 216 control film without no phosphor added. (Middle) Film with a 1:4 EY4453 to Qsil 216 ratio by weight. (Right) Film with a 1:2 EY4453 to QSil 216 ratio by weight. Note air bubbles are present in all films.

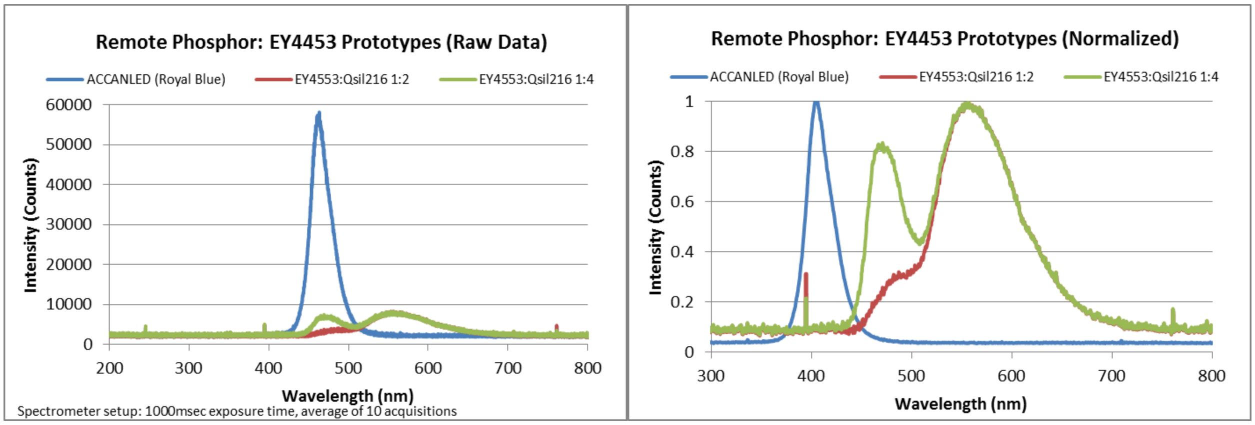

Figure 3: EY4453 White Emitting Phosphor Prototypes. (Left) Raw emission spectra, 1s exposure time, average of 10 exposures, filtered with a 5 bin boxcar. (Right) Normalized emission spectra.

Intematix LWR6832 Phosphor: Long Wavelength Red (peak emission at 660nm)

Coated with QSil 216 as an encapsulant, several 0.9mm thick films were made at various phosphor to encapsulant ratios (see Figure 4). A Blue XCANLED (447nm peak) was used for testing, and emission spectra taken using an Ocean Optics spectrometer. The resulting emission was stable over quite a broad range of concentrations, only showing saturation (blue light present in the emission spectra) for ratios of 1:20 or lower by weight. Figure 5 (below) shows the inside view of the test jig with the 1:10 film and the XCANLED lit up, and Figure 6 (below) shows the emission spectra of the films.

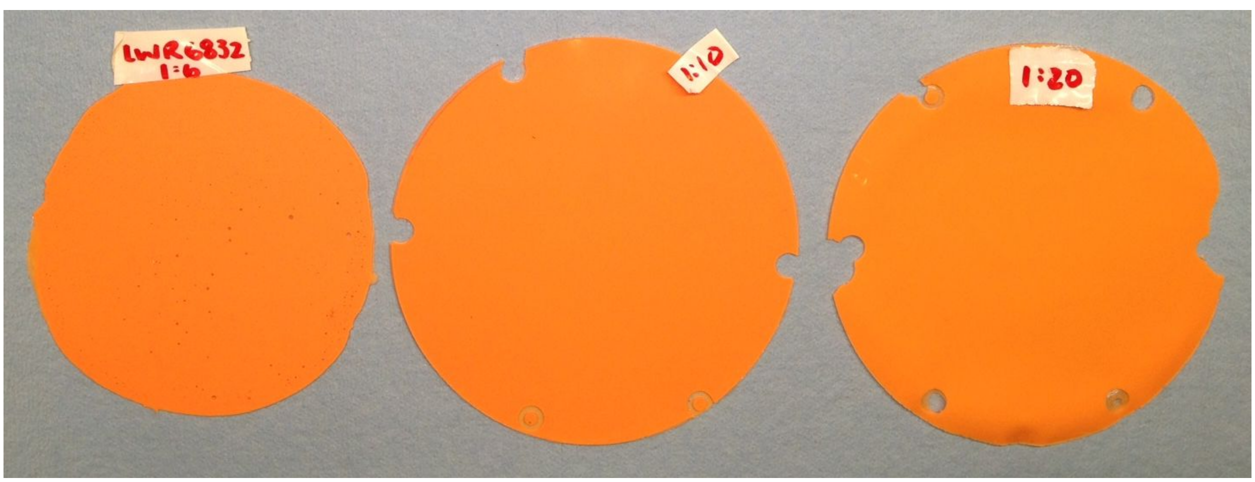

Figure 4: LWR6832 phosphor films. (Left) 1:6 Phosphor to QSil 216 ratio by weight, (Middle) 1:10 by weight, (Right) 1:20 by weight. Note general lack of bubbles in the 1:10 and 1:20 films as fabrication techniques improved.

Figure 5: View inside of test jig for 1:10 LWR6832 phosphor film with Royal Blue XCANLED turned on.

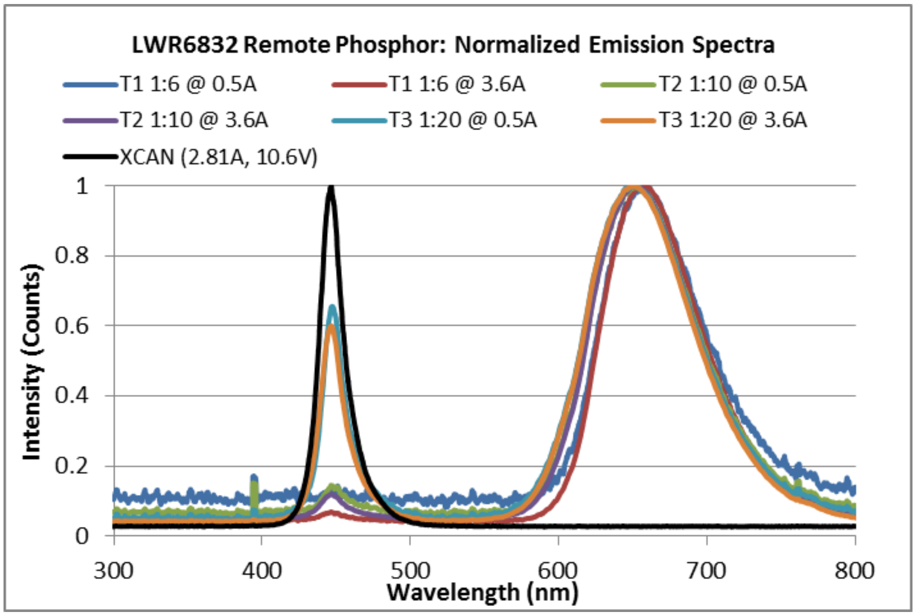

Figure 6: Normalized emission spectra for Intematix LWR6832 phosphor films mounted on the exterior window of a Royal Blue XCANLED (peak emission at 447 nm). Blue light is present in the emission spectra only for phosphor loadings of 1:20 phosphor to Qsil 216 encapsulant by weight.

In an attempt to investigate saturation behaviour of the phosphor, the 1:10 and 1:20 films were mounted directly on top of the LEDs (Figure 7) to provide a much higher (>10 fold increase) optical power density in the phosphor film. If the phosphor is being saturated, the relative intensity of the Red and Blue peaks would change with LED light output. No sign of this is observed (Figure 8), so it can be concluded that for the 1:20 film the phosphor layer is not being saturated, but instead the blue emission is from light that passes through the film without hitting a phosphor particle. This is consistent with the fact that the color temperature for white LEDs is stable across a wide range of drive currents – the blue part of the spectrum is not from saturation of the phosphor but rather line-of-sight gaps in the coating.

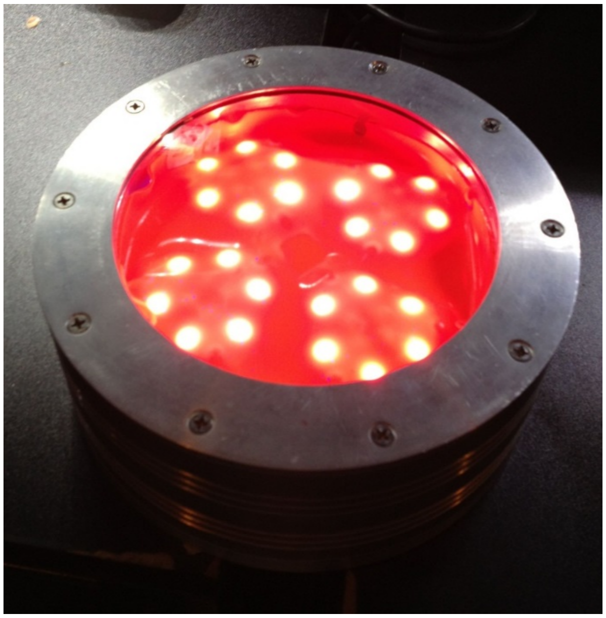

Figure 7: Royal Blue XCANLED with 1:20 LWR6832 to QSil 216 film installed directly on top of LEDs.

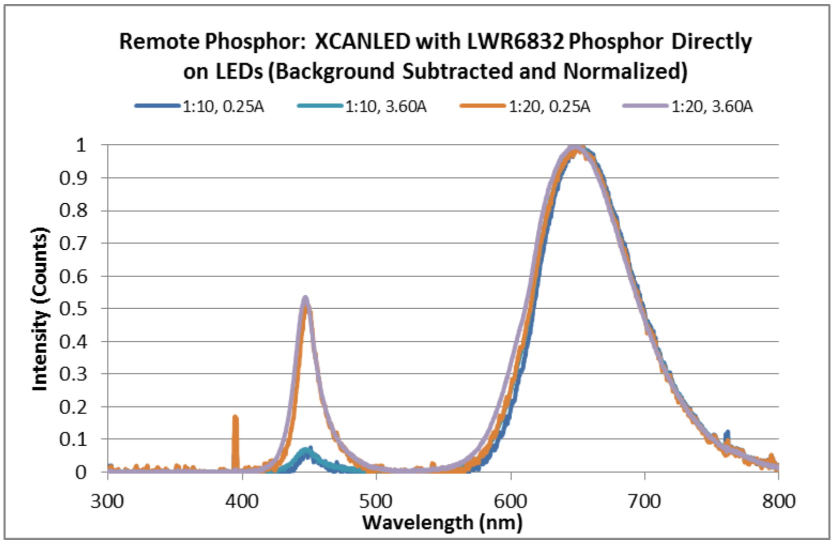

Figure 8: Normalized emission spectra for Intematix LWR6832 phosphor films mounted directly on the LED primary optics of a Royal Blue XCANLED (peak emission at 447 nm). If the phosphor is saturating, a difference in peak heights between the blue and red peaks would be expected for each film between the low and high drive currents.

Assessment of Viability for Nemalux Fixtures:

Given the substantial energy loss in the phosphor layer (estimated in the 30% to 50% range) there will be substantial heating in the film. For the Light Cannon project the optical power incident on any phosphor layer will be extreme enough that to heat the phosphor layer beyond its maximum temperature of 170°C. It can be concluded that phosphors are not a suitable technology for the Light Cannon project. However, for custom wavelength products in horticultural, signage, or scientific applications remote phosphors may be a viable and attractive technology.

One potentially attractive product idea is to create an adjustable color temperature fixture based on a phosphor layer capable of being saturated. The idea is to build a fixture such that at medium power the phosphor layer is close to saturation. To increase the color temperature of the fixture half of the LEDs would be dialed back in power, with the remaining half increasing their output and saturating the phosphor layer directly in front of the LED. The total light output could be kept constant, but there would be a tunable shift in color temperature. This could be an elegant approach to create a circadian rhythm matching fixture. However, in order enable this we would need to move to a much smaller pigment size, or switch to a fluorescent dye based system. Further work would be required to assess if these materials are readily available.

Legal Liability:

Several companies have heavily patented the use of remote phosphors in lighting applications, most notably Cree and Intematix. Most of these patents are broad enough to cover any LED use of phosphors. Additionally there are numerous application-specific patents out there by a wide range of companies. LEDs Magazine has a good overview article on the patent landscape for remote phosphors here: http://ledsmagazine.com/features/9/7/1. Cree is asserting a patent on remote phosphor based LED luminaires and bulbs, the rights to which are not automatically granted with the purchase of Cree royal blue LEDs. Cree's licensing program is detailed on the following page: http://www.cree.com/about-cree/licensing/licensing-programs. Intematix is also asserting rights to a number of patents on remote phosphor designs, their list of patents and patent applications can be found here: http://www.intematix.com/technology/intellectual-property/ip-chart. It appears that use of the Intematix Chromalit line of remote phosphor products includes right-to-use, and that Intematix will provide legal defense in event of a lawsuit based on rights to the remote phosphor technology. It is not clear whether this support is provided for use of raw phosphors coated by Nemalux. Nemalux will need to ensure that it carries out a patent search and assesses right-to-use prior to product launch for any remote phosphor application.