APPLICATIONS NOTE

Considerations for Blending LED Phosphors

January 2013

Introduction: Phosphor is used in conjunction with blue emitting LEDs to create white light or other desired color points. While there are some instances where the use of a single phosphor will achieve the desired result (i.e. cool white, mid to low CRI LEDs), in many cases it is necessary to use more than one phosphor to achieve a desired result. For example, high efficacy, warm white, high CRI, and tight color binning when using a broad distribution of blue pumps must be achieved through blending phosphors.

Contents

Basic principles of white light construction 2

Phosphor blending and color point targeting 4

Blending procedure 7

Conclusion 8

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Basic principles of white light construction

Broadly speaking, the color points achievable by a particular phosphor/blue LED mix will fall on a line drawn between the CIE[1] coordinates of the pure blue LED and the saturated phosphor point. Increasing the amount of phosphor in the optical path will shift the color point towards the saturated phosphor's coordinates. To illustrate, Figure 1 shows a 454 nm dominant wavelength blue pump's coordinates (ca. x=0.154, y=0.025) with three incremental additions of NYAG4454 shifting the color point towards the saturated point (x=0.444, y=0.536)[2].

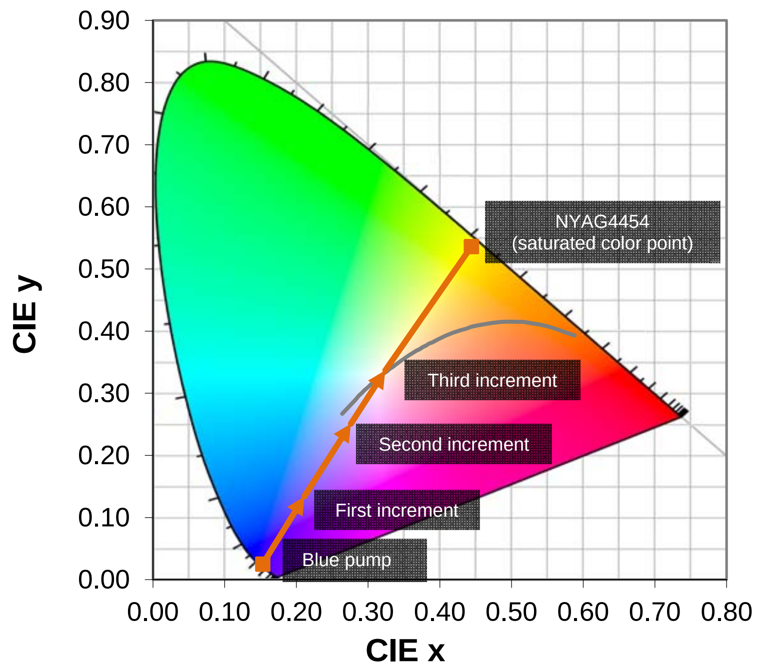

Figure 1 CIE 1931 color space diagram showing a blue pump (lower left, 454 nm dominant wavelength), three incremental additions of NYAG4454, and the saturated color point of NYAG4454 (upper right).

As you change the wavelength (and thus CIE xy) of your blue LED, the intersection of the blue LED/saturated phosphor line with the black body curve, which defines your "white" CCT, will also change. Figure 2 outlines the wide variance in CCTs achievable using a single phosphor (NYAG4454 in this example), shifting blue LED from 445 nm to a longer 465 nm wavelength changes the resultant CCT from 5000K (CRI~64) to 6200K, (CRI~76), and results in about 5% less phosphor usage.

[1] This document will address color space with respect to the CIE 1931 convention using x and y, however the discussions are just as applicable using the 1976 convention with u' and v'.

[2] It should be noted that a linear CIE versus solids loading trend is only a rough estimation. The actual curve is not linear; a red shift occurs as solids loading increases. In most cases a slightly longer wavelength phosphor is required to hit the desired color point.

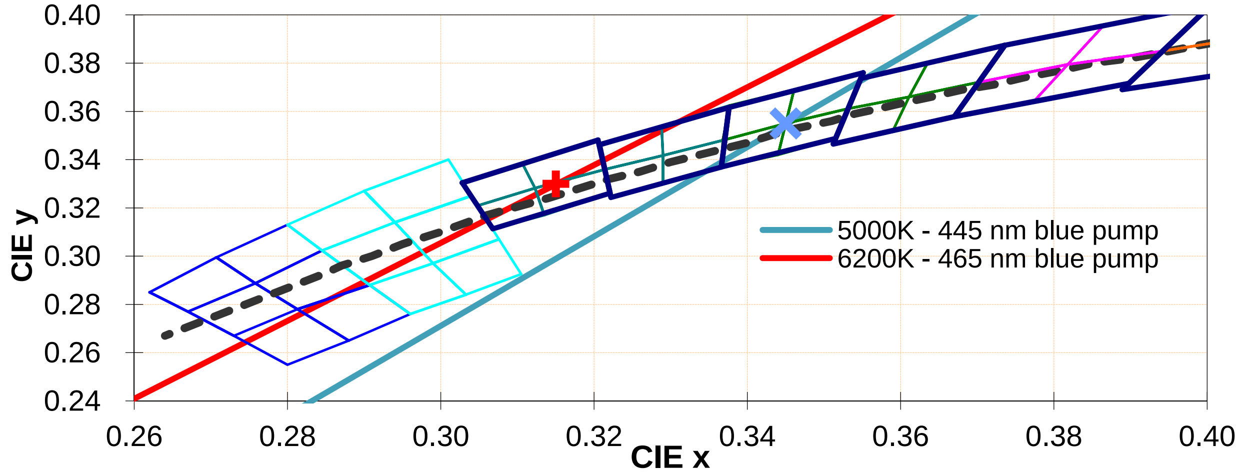

Figure 2. Effect of changing blue LED wavelength on CCT and phosphor usage in making a white LED.

As the blue wavelength changes, the phosphor's color must also shift to maintain the same color point of the final product white LED. Figure 3 shows the saturated color points of several phosphor materials (squares and triangles) as well as several trend lines from blue LEDs (445-465 nm dominant), through CIE xy 0.300, 0.300 point, to the saturated color necessary from the phosphor (or phosphor blend).

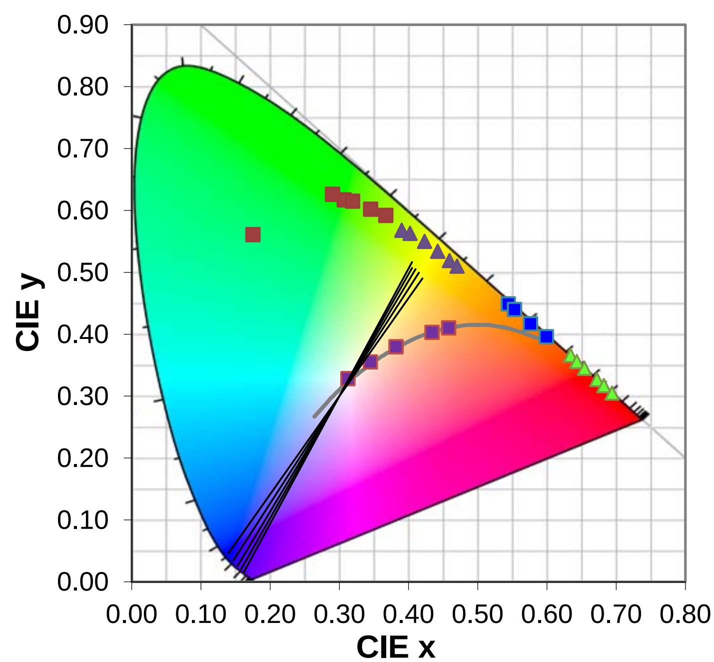

Figure 3. Required phosphor color changes as a function of blue LED wavelength changes.

To some degree, the CIE xy value attainable with a phosphor is independent of the peak shape; that is, very dissimilar phosphor peaks can produce the same CCT. For example, in Figure 4 NYAG4454 and EY4453, have different emission spectra (different peak wavelengths, 558 nm vs. 565 nm and peak widths, 115 nm vs. 92 nm). However, because their saturated CIE xy values are nearly identical, the CCT outcomes with different blue pump wavelengths outlined in Figure 2 are identical. The CRI values, however, are more a function of the peak shape/width, for example 5000K CRI with EY4453 is 58 and 6200K CRI is 67, which falls between 6 and 10 points lower than NYAG4454.

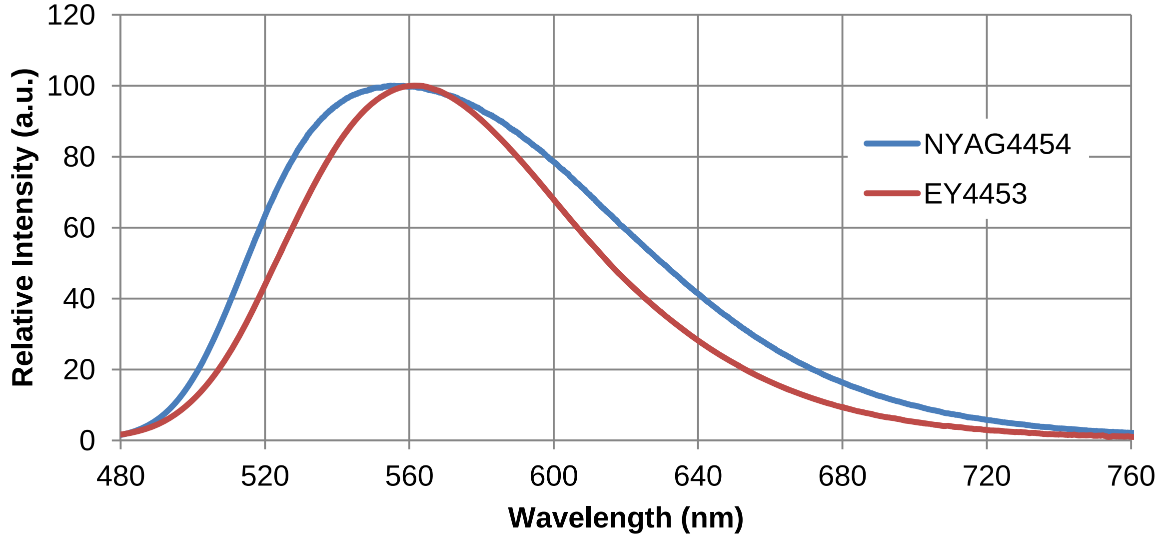

Figure 4. Different phosphors with different peak shapes and peak wavelength values, but nearly identical saturated CIE xy values.

Phosphor blending and color point targeting

Similarly, this CRI difference extends to blends. The same two phosphors when blended with a red phosphor to a warm white solution may also exhibit differences. For example, Y3957 (0.390, 0.568), and GAL545-L (0.392, 0.556) with ER6436 at 3000K will yield CRIs of 75 and 80 respectively. The difference in CRI here is generally attributable to the FWHM of 87 nm for the Y3957, compared to 112 nm for GAL545, as well as the increased emission by the phosphor on the blue-green side of its emission peak.

Generally speaking, any blend of phosphors can be treated as if it were a single phosphor, thus the ratio of phosphors in the blend needs to be adjusted to continue to meet a target CIE value. For example, Intematix has compiled Table 1 which illustrates how a blend of yellow silicate phosphors needs to be adjusted with changing blue LED wavelength in order to meet the CIE xy = 0.3,0.3 requirement for some display backlighting units (illustrated in Figure 3).

Table 1. Blend ratios of Intematix yellow silicate phosphors required to achieve CIE xy= 0.300, 0.300 with specified blue wavelengths.

LED Chip (nm)			EY4156	EY4254	EY4453	EY4651	EY4750
447.5	~	450.0	30%	70%			
450.0	~	452.5		100%			
452.5	~	455.0		50%	50%		
455.0	~	457.5			100%		
457.5	~	460.0			70%	30%	
460.0	~	462.5				70%	30%

Figure 5, which shows trendlines from a 454 nm blue pump through several target CCTs on the black body locus and out to saturated phosphor points, illustrates targets for general lighting applications. From the figure, it is clear that CCTs of 4000K and higher are attainable with a

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single phosphor (at least with the illustrated blue pump) but CCTs lower than 4000K, such as 3000K, cannot generally be achieved with a single phosphor. A blend of any phosphor “above” the trend line with any phosphor “below” the trend line will enable the desired CCT to be achieved. For example, GAL545 or NYAG4156 can be combined with any red phosphor to obtain any of the four example CCTs illustrated in Figure 5 because a combination of the yellow-green phosphor and red phosphor can obtain the required CIE to match the saturated end point. The figure has four lines illustrating a common blue pump (dominant wavelength 454 nm), and four common CCT targets (from left to right 6500K, 5000K, 4000K and 3000K). The extensions of these lines to the right hand boundary of the color space show where the saturated phosphor color points should be.

Using the example laid out in Figure 5, phosphor blends to make white light of varying CCTs using a 454 nm dominant wavelength blue LED would require saturated phosphor blend color points as outlined in Table 2.

Table 2. Selected CCTs and Approximate Phosphor Color

CCT (K)	Saturated Phosphor CIE x,y
6500	0.430, 0.550
5000	0.440, 0.540
4000	0.460, 0.510
3000	0.490, 0.470

As noted earlier, GAL545 has a value of 0.392, 0.556, and when GAL545 is coupled with RR6436, 0.641, 0.359, the resultant blend will have a color point:

CIE x= “a” x CIE x_{GAL545} + “b” x CIE $x_{RR6436;}$ CIE y = “a” x CIE y_{GAL545} + “b” x CIE y_{RR6436},
a and b are the weighted percentages of GAL and red phosphors, i.e. a+b=100%

If there were no interactions between the phosphors (i.e. absorption of blue, green and yellow by orange or red phosphors) then this method to estimate blend ratios based on the xy coordinates of the saturated phosphors and simply the amount of phosphor would work well. Unfortunately, most commercially available orange and red phosphors do have such interactions, meaning that complex modeling, or trial and error methods must be employed. (Often the phosphor manufacturer will be able to provide guidance in this matter.)
Taking a typical warm white LED build (3000K, CRI~80), the recommendation is to use Intematix GAL545 + Intematix RR6436. Based solely on the CIE values of the green and red phosphors the ratio would be expected to be around 60/40 as noted above, however, because of the cross excitation (the red phosphor is excited by both the blue LED and the emission of the green phosphor) the real ratio is closer to 88/12.

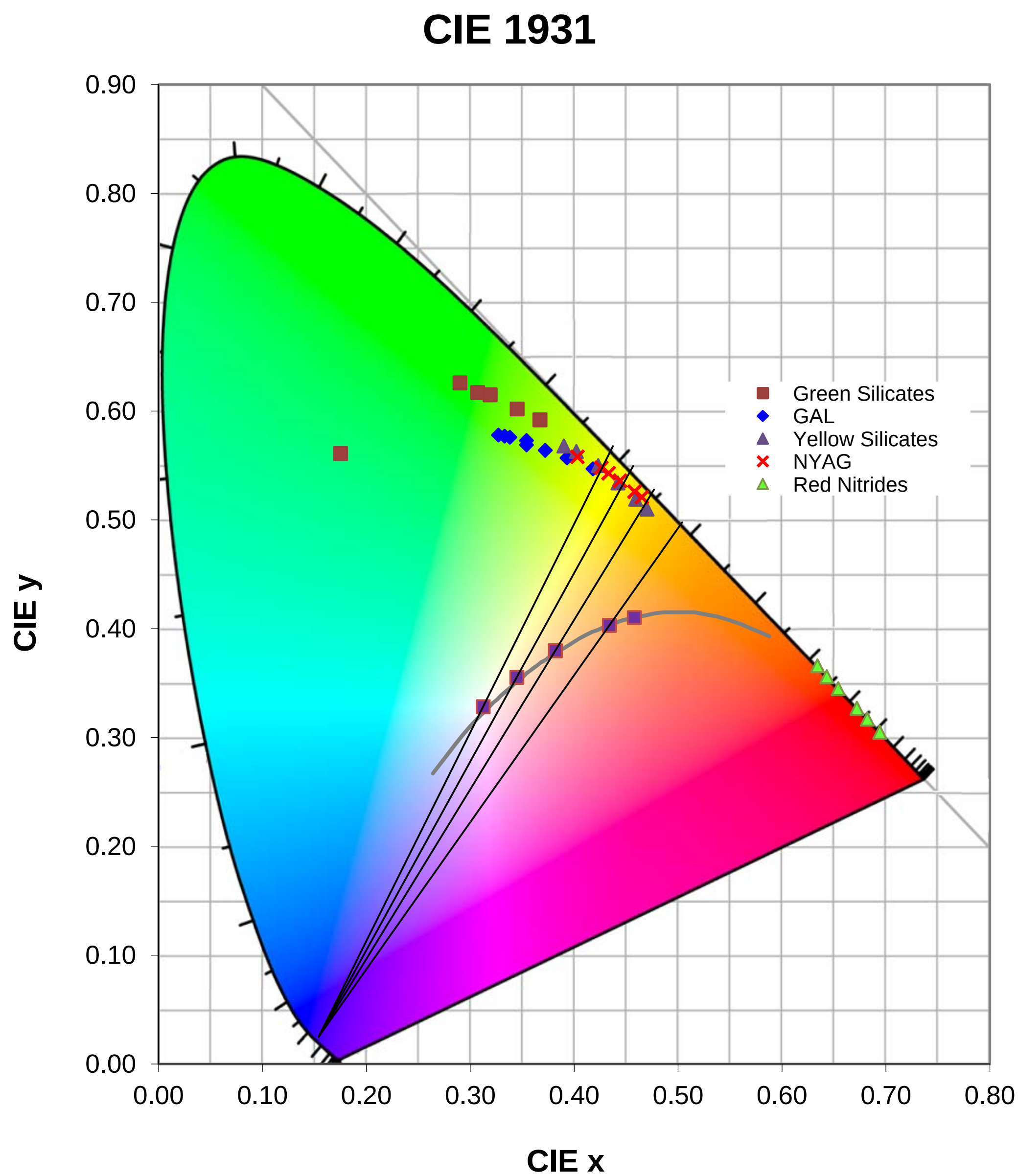

Figure 5. Trendlines showing required saturated phosphor color points to achieve 6500K, 5000K, 4000K and 3000K with a selected blue LED wavelength.

Changing the blue wavelength can have several effects. First, the required ratio of phosphors will change, typically, as the blue wavelength is shortened the amount of red phosphor required will decrease, so the GAL545/RR6436 ratio will shift from 88/12 when using a 455 nm blue pump, towards 89/11 when using a 450 nm blue pump. A second effect of varying the blue wavelength is that the CRI will change. The same blue pump shortening that changes the GAL/RR ratio will also lower the CRI; the exact magnitude is a function of many factors, but for purposes of further illustrating the importance of proper phosphor selection, let's say that the blue wavelength shift drops the CRI from ~81 to ~79. This shift would drop it below a common lighting threshold of CRI~80, and it would become necessary to shift to GAL540+RR6436 or GAL545+ER6535, in order to keep the CRI > 80.

Table 3. Phosphor Blend Ratios for 3000K CCT with Resulting CRI Values

Phosphor 1	Phosphor 2	@ 461 nm		@454 nm	
		Ratio 1/2	CRI (CIE y value)	Ratio 1/2	CRI (CIE y value)
GAL545	RR6436	84/16	82.0 (y=0.406)	88/12	80.5 (y=0.401)
GAL540	RR6436	83/17	85.0 (y=0.404)	87/13	82.8 (y=0.403)
GAL535	RR6436	83/17	84.7 (y=0.406)	84/16	83.9 (y=0.407)
GAL530	RR6436	84/16	85.6 (y=0.405)	-	-
GAL535	ER6535	84/16	92.6 (y=0.400)	-	-
	ER6634	85/15	98.0 (y=0.401)	84/16	96.5 (y=0.407)
	LWR6931			94/6	92.3 (y=0.400)
NYAG4355	ER6535	84/16	81.5 (y=0.403)	-	-
	ER6634	85/15	86.4 (y=0.405)	-	-
GAL525	ER6634	-	-	88/12	96.7 (y=0.406)
GAL545	ER6535	-	-	87/13	84.7 (y=0.400)
	ER6634	-	-	90/10	88.8 (y=0.405)
	LWR6733	-	-	92/8	89.4 (y=0.404)
NYAG4454	RR6436	-	-	88/12	71.7 (y=0.405)
	ER6634	-	-	83/17	77.9 (y=0.405)
	LWR6931	-	-	95/5	78.8 (y=0.403)
GAL525	ER6436/ LWR6931	-	-	90/6.3/3.7	98.0 (y=0.399)

Note: CIE x values are fixed at 0.437. CIE y values are shown to illustrate the effect in CRI

Blending procedure

Blending the phosphor starts with the task of determining the proper blend ratio between one or more phosphors and the encapsulant used to deliver the phosphor to the LED.

a. An encapsulant (typically, a two part, thermally cured system) is mixed thoroughly in the appropriate ratio and degassed by vacuum and agitation.
b. A measured amount of encapsulant (often 100 mg) is placed on a microscope slide.
c. A pre-calculated amount of phosphor(s) is (are) placed on the slide to achieve the desired ratio between phosphors, and the desired ratio between phosphor and encapsulant.
d. The phosphor and encapsulant are mixed thoroughly with a wooden dowel.

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e. The resultant phosphor slurry is placed into the test LED package using a very small applicator, such as a 26 gauge tuberculin needle to properly fill the package, and achieve the desired color point.
    a. Phosphor and/or silicone amounts can be varied until the desired outcome is achieved.

On the larger scale (i.e. up to 10 g of phosphor), blending of phosphor powders can be achieved by mixing pre-measured amounts of phosphors into a bottle, placing the lid on the bottle, and manually shaking and rolling for a few minutes (2-3). Mixing time should be increased as the amount of phosphor being mixed increases, for example, 10 minutes for 100g of phosphor. For quantities over 100g, the bottle containing phosphor can be placed in a mechanical agitator, such as a roller mill (without the use of milling balls), for 1 – 5 hours for quantities of 0.5 – 10 kg.

If using a mixing system designed for phosphor slurry preparation, then the individual phosphors can be placed in the preparation without the need for premixing. It is not uncommon for the order of addition of phosphor(s) and encapsulants to have an impact on the homogeneity of mixing, so some experimentation may be required.

Conclusion

With a wide variety of phosphor choices available, adept blending strategies enable LED manufacturers to achieve nearly any desired color point at any desired CRI. Such strategies start with selection of the phosphors, followed by blending and finally testing.

Phosphors Referenced

Product	Material	Peak Emission (nm)	CIEx	CIEy
GAL525	Aluminate	525	0.338	0.576
GAL530	Aluminate	530	0.347	0.573
GAL535	Aluminate	534	0.354	0.571
GAL540	Aluminate	540	0.372	0.564
GAL545	Aluminate	545	0.395	0.555
NYAG4355	Garnet	541	0.426	0.548
NYAG4454	Garnet	558	0.444	0.536
EY4156	Silicate	550	0.402	0.563
EY4254	Silicate	558	0.423	0.550
EY4453	Silicate	565	0.442	0.534
EY4651	Silicate	569	0.459	0.519
EY4750	Silicate	574	0.470	0.510
RR6436	Nitride	630	0.641	0.359
ER6535	Nitride	640	0.641	0.358
ER6634	Nitride	650	0.670	0.330
LWR6733	Nitride	655	0.666	0.333
LWR6931	Nitride	670	0.694	0.305

For more information, visit **www.intematix.com**
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