WHITE PAPER

Spectral Pure Technology

Introduction

Smartphones are ubiquitous in everybody's daily lives. A key component of the smartphone is the camera, which has gained market share over Digital Still Cameras due to its convenience. This camera is now the most commonly used camera for the everyday spontaneous pictures, such as selfies, family and friends pictures and for sharing. In addition to the well-known resolution increase of cell phone cameras, we also see a strong projected increase of dual camera smartphones in the market (see Figure 1); this is another indication of the importance of the camera function in phones.

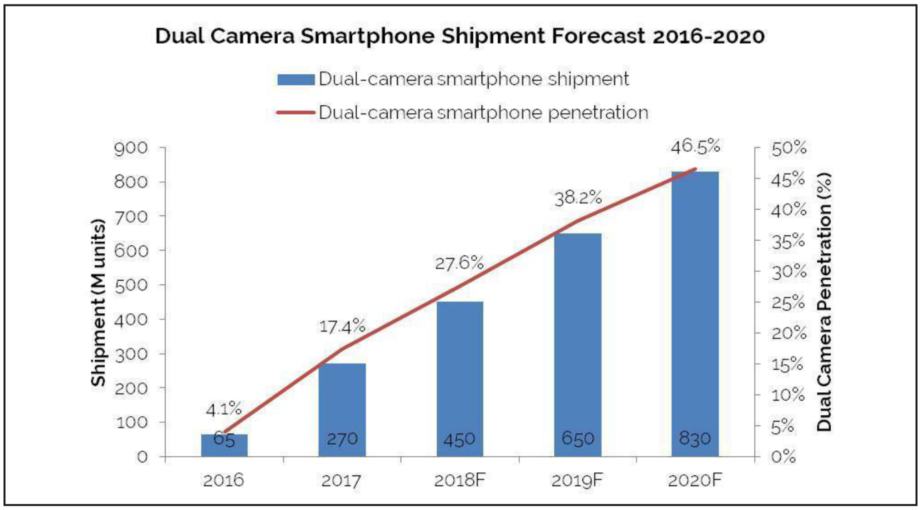

Figure 1. Expected increase of dual camera in smartphone (Isaiah Research Group).[1]

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1. Picture Quality

The major factors contributing to the quality of a picture where lighting plays a role are signal to noise ratio and color reproduction. Once the signal to noise ratio is sufficient, color reproduction optimization is the most critical (see Figure 2).

The color of an object is determined by:

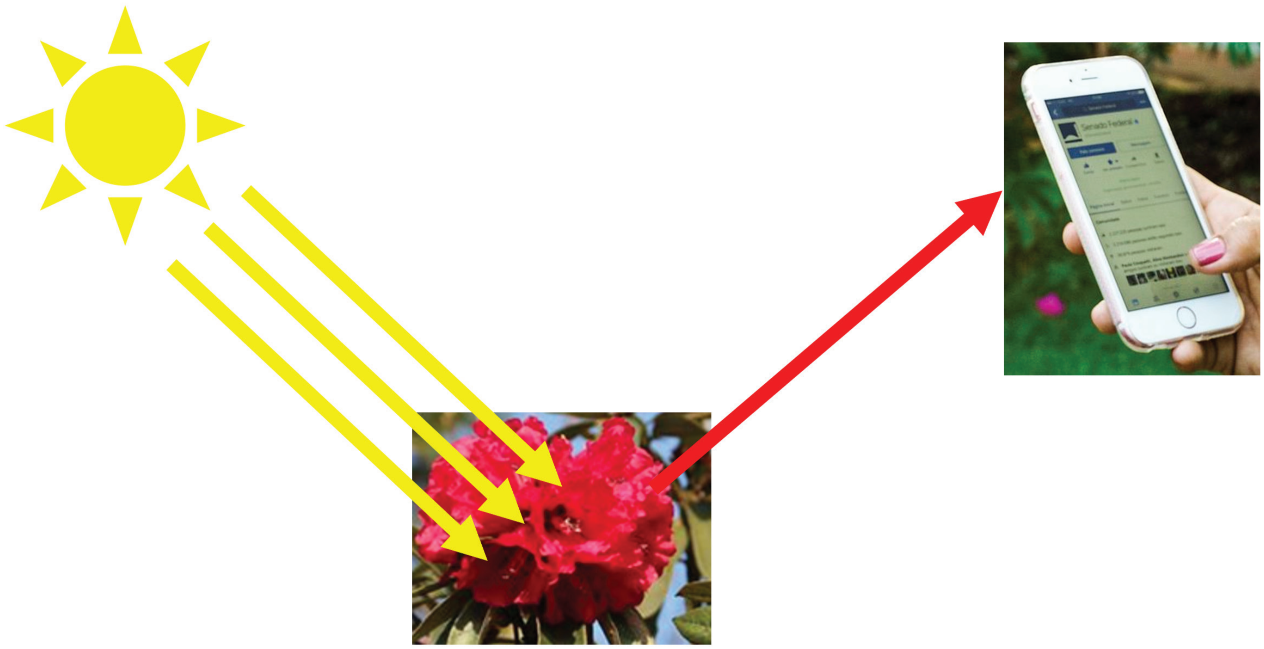

Figure 2. Elements contributing to the color reproduction – spectral properties of the light source, the reflectance properties of the object and the sensor spectral sensitivity.

When a flash is used, the spectrum of the LED can be tuned. This white paper addresses how to best tune the spectrum of an LED used in a camera flash module.

2. Tuning the LED's Spectral Emission Properties

An LED emitting white light is fabricated by coating an InGaN-based die emitting blue light (the blue pump) with a phosphor coating. When the light hits a phosphor molecule, the phosphor absorbs a portion of the blue light and converts it to light of a lower wavelength. The concentration and layer thickness of the phosphor coating, for instance, using a YAG phosphor to produce yellow light, can be tuned to still transmit some blue light through the phosphor. The transmitted blue light and phosphor-converted yellow light combine to give white light with a relatively high color temperature (6000K). As the emission spectrum shows (see Figure 3), there are blue and yellow peaks, but the cyan, green and red light color reproduction is relatively poor—the human observer color rendering index (CRI) is only 60.[2] To increase CRI, additional phosphors must be mixed into the coating.

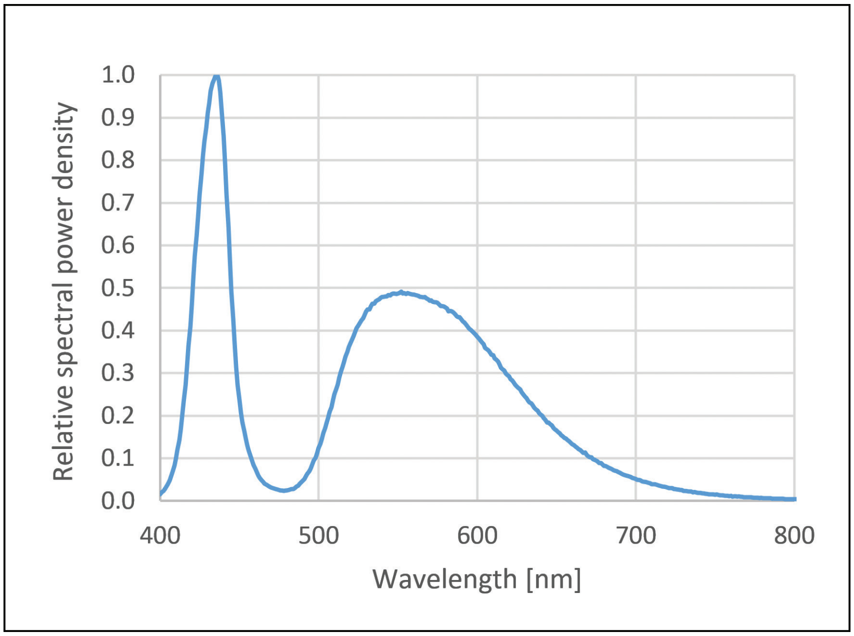

Figure 3. Typical white LED spectrum with blue pump and single YAG phosphor.

Lumileds has in-house phosphor research, development and manufacturing departments. In parallel, the R&D team is always scouting the world for new phosphors (see Figure 4).

Typically, each new phosphor will be characterized for its spectral properties, temperature dependence, efficiency and reliability. If the parameters appear promising, the phosphor is added to the modeling database—from the characterization data, a phosphor model is generated, which then models the LED properties when multiple phosphors are integrated in one LED package. An LED build validates the model and tests the packaged device. If the LED modeling and testing is successful, the phosphor is released for further spectral optimization.

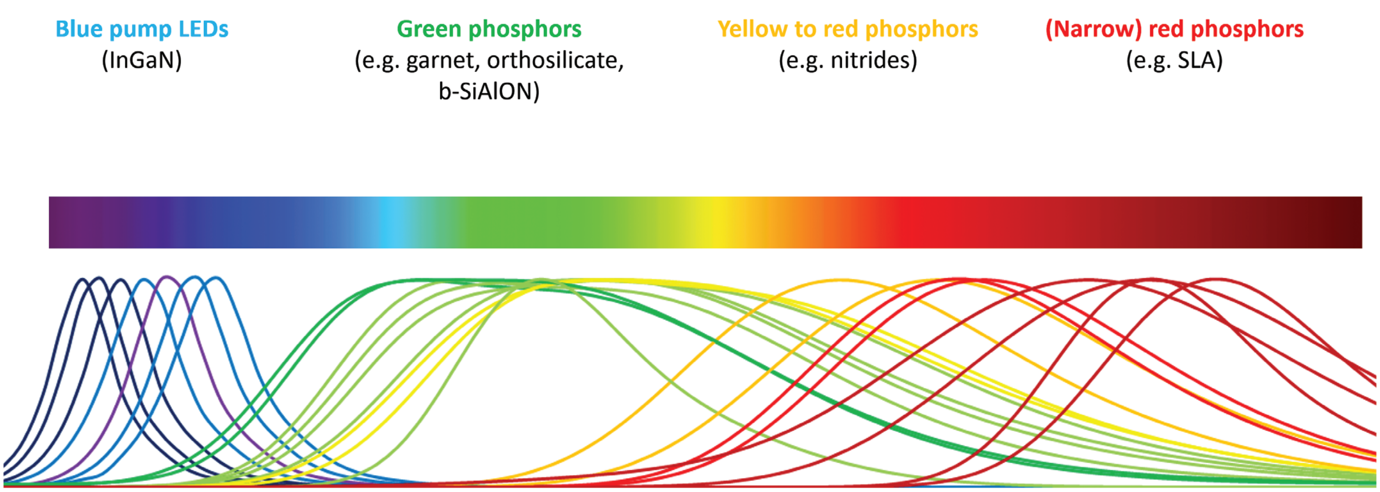

Figure 4. Phosphor types.

3. Tuning the Spectrum – Introducing CCI

Human color vision is based on the wavelength-dependent sensitivity of the human eye's photodetector cone cells, where three different types have been identified. Their peak absorption is shifted with respect to each other, with the highest sensitivity in the short wavelengths of the visible spectrum, followed by the mid-range and longer wavelengths. The Commission International d'Éclairage (CIE) first defined the human x and y color space in 1931 by defining three color matching functions, which was X, Y, Z, representing the photosensitivity of the three cone cells (see Figure 5). When artificial lighting came into general use, the question of color reproduction as seen by humans was analyzed and the color rendering index, R_a, was defined (current version: CIE 13.3 1995).

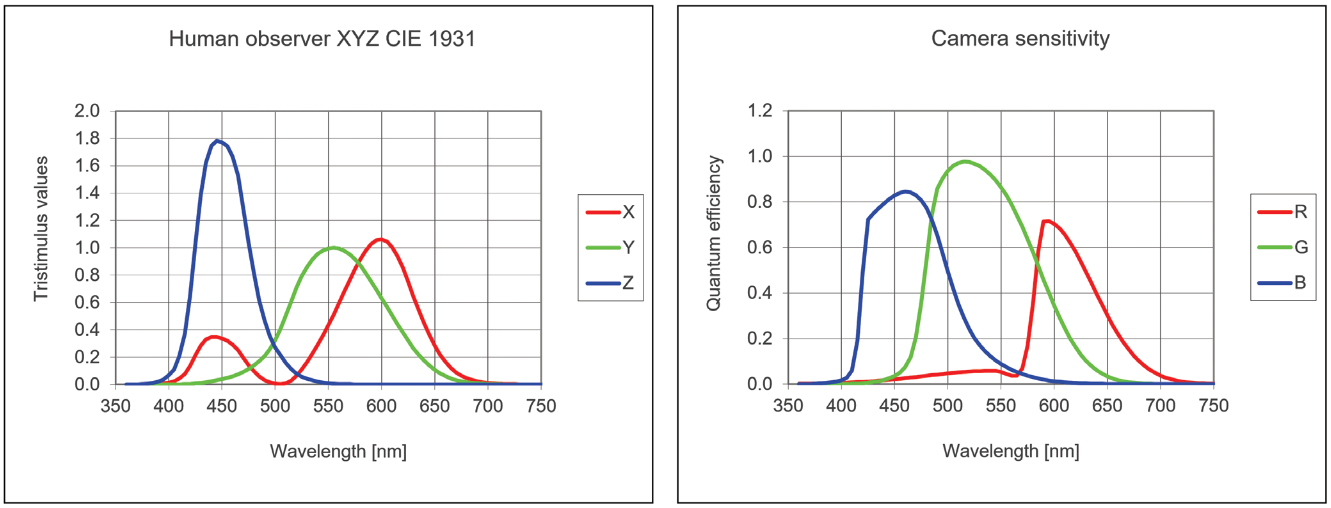

Figure 5. Left: color matching functions x, y and z (CIE 1931); right: camera sensitivity curves R, G and B (based on IMX214).

Figure 5 shows the CIE human observer color matching functions next to a typical camera spectral sensitivity curve. Clearly, the spectral sensitivity is different between the human observer and the camera and classifying the illuminator by the human color sensitivity will not provide a good representation of the color reproduction of a camera.

The sensor of a color camera has neighboring pixels covered by one of the three color filters, red (R), green (G) and blue (B). Typically, the pixels are distributed according to the Bayer Pattern (see Figure 6). These pigment-based filters transmit only red, green or blue light, respectively, and absorb light of other colors. In combination with the silicon photosensitivity, the sensor's quantum efficiency vs. wavelength can be determined. As the commonly used color filters let infrared (IR) light pass, the camera manufacturer adds an IR filter to block that light to avoid saturation of the pixels by this part of the spectrum.

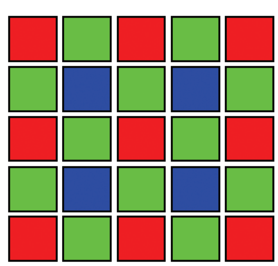

Figure 6. Bayer Pattern

To improve the color performance of an illuminator for camera applications, in a similar manner to CRI, Lumileds defines the Camera Color Index (CCI) and optimizes the camera flash illumination spectrum along this metric. The first step involves determining the Correlated Color Temperature (CCT) of the light source under test. Secondly, we calculate the spectrum of the reference spectrum, the black body radiator spectrum at the same CCT. The third step is to calculate with the camera sensitivity curves R, G, B and the Macbeth color chart, the response from the light source under test and from the reference spectrum. This is the raw response of the sensor when illuminated by either the light source under test or the reference spectrum. The next step is to isolate the color differences, Δ_k, by calculating the distance in the r, g space as follows:

$$r = \frac{R}{(R+G+B)} \quad \text{and} \quad g = \frac{G}{(R+G+B)}$$

Which would be for each color patch (index k) of the Macbeth chart (see Figure 7).

$$\Delta_k rg = \sqrt{\left(r_{ref,k} - r_{LED,k}\right)^2 + \left(g_{ref,k} - g_{LED,k}\right)^2}$$

Here, "ref" stands for the reference light source and "LED" stands for the light source under test.

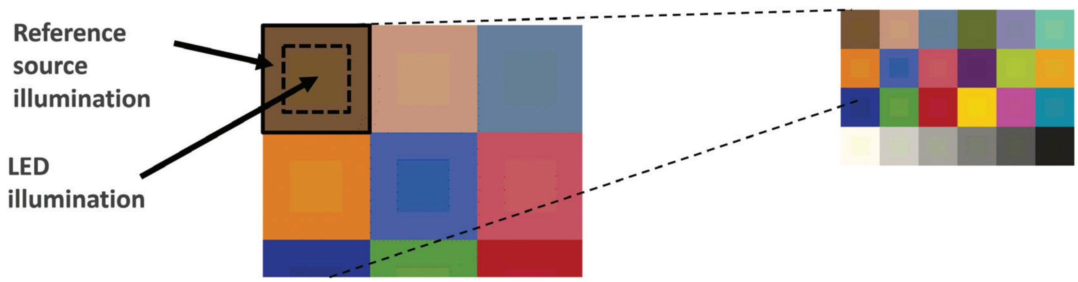

Figure 7. Visualization of Macbeth color difference with two light sources.

Finally, CCI will equal (100- $\Delta_k$average) or 100 minus the average of these differences. The best CCI is 100 when the spectrum is equal to the reference spectrum. The coefficient 750 in front of the r, g difference is chosen to result in numbers around 70 for typical flash LEDs with 80CRI and to show sufficient sensitivity for phosphor changes to enable easier optimization:

$$CCI = mean_{\,k}(100 - 750\,\Delta_k\, rg)$$

Figure 8 shows the calculation steps for CRI versus CCI. The main difference is for CCI to work in the R, G, B camera color space and compare color reproduction with respect to the Macbeth colors referenced.

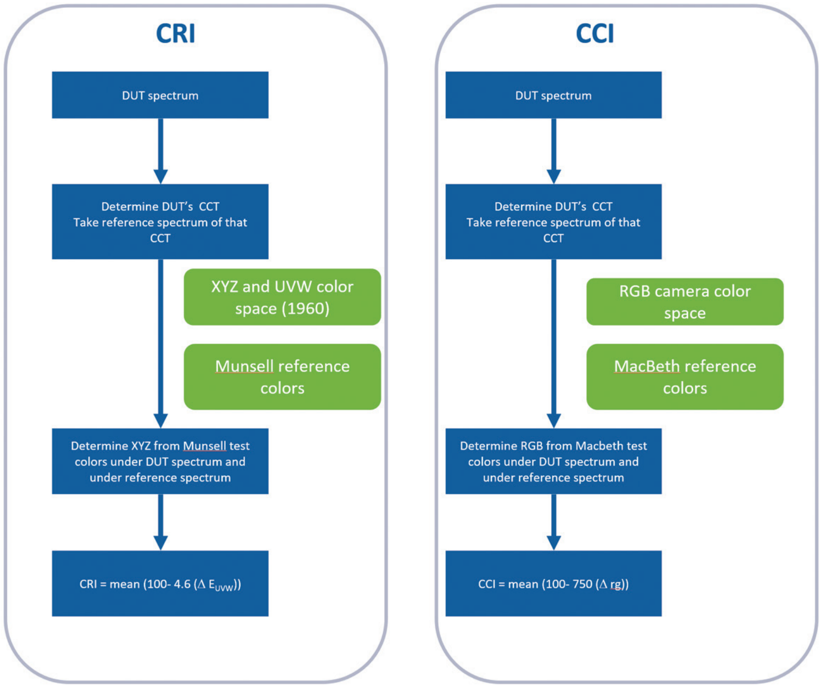

Figure 8. CRI vs. CCI procedure.

Figure 9 shows the CCI result for the achieved spectrum, which Lumileds is calling **Spectral Pure**, compared to 80CRI and 90CRI LED spectra at a correlated color temperature of 4500K.

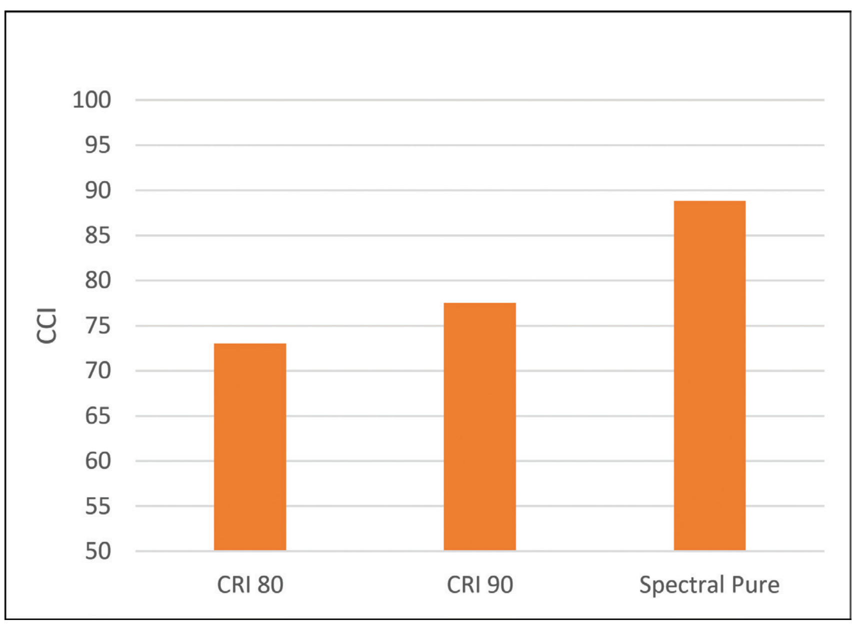

Figure 9. CCI results for typical camera flash LEDs and Spectral Pure.

We pursued a similar calculation with respect to the Television Lighting Consistency Index (TLCI)[3] and the ability to predict the reproduced color for broadcasting. TLCI mimics the path from camera detection to display reproduction. However, because the color filters from TV cameras are different from those in smartphones and the image pipeline in smartphones is very sophisticated, Lumileds chose to limit the comparison up to the sensor level. In addition, if the detected raw signals are matched, the color rendering results after processing must be the same.

4. Color Reproduction Validation

We purchased commercially available high-end smartphones for a side by side comparison of the newly optimized phosphor mix for LUXEON Flash 9X with Spectral Pure Technology (see Figure 10 and Figure 11).

We organized typical scenes for flash pictures and mounted the phones on tripods. We blocked the phones' built-in camera flash and illuminated the scene using either an 80CRI camera flash LED or the LUXEON Flash 9X with Spectral Pure Technology. For a distance of up to about 1.5 meters from the phone, the flash illumination is the predominant light in the room with a low ambient light level. We utilized the phones' camera app and all settings were left on automatic.

Figure 10. Picture taken under camera flash LED illumination, 4500K CCT, 80CRI.

Figure 11. Picture taken under LUXEON Flash 9X with Spectral Pure Technology, 4500K CCT.

The comparison between Figures 10 and 11 shows that skin colors are more pleasant and healthy looking in Figure 11, the jean jacket's blue color is rendered as a more open and fresh color, and the wood of the table and the wall appears more vibrant in the photo taken using the LUXEON Flash 9X with Spectral Pure Technology.

5. Summary

As picture taking with smartphones becomes ubiquitous, producing the highest quality pictures has become an important optimization target for flash LED manufacturers. Color reproduction depends on the illumination, the object reflectance and the detector used to record the scene. An LED's spectral emission properties can be carefully tuned to optimize the illumination. For this purpose, a metric, the camera color index (CCI), is presented, which compares the RGB response of the camera under camera flash illumination to illuminance under the reference black body radiator. This metric is similar to CRI developed for the human observer.

Lumileds used this procedure to optimize its phosphor mix and develop LUXEON Flash 9X with Spectral Pure Technology. Pictures taken using two commercially available high-end smartphones with this camera flash LED showed more vivid and detailed colors than pictures taken with an 80CRI flash LED. There is particular distinction with respect to the vibrancy of the skin tones, the vividness of red and blue colors and the richness of wood grains.

6. References

1. IF News, *"Dual Camera Smartphone Shipment Forecast 2016-2020,"* Isaiah Research Report
2. CIE. 1995. Method of Measuring and Specifying Colour Rendering Properties of Light Sources. CIE 13.3-1995. Vienna, Austria: CIE Central Bureau.
3. EBU - Technology & Innovation, *"Television Lighting Consistency Index 2012,"* https://tech.ebu.ch/tlci-2012

About Lumileds

Companies developing automotive, mobile, IoT and illumination lighting applications need a partner who can collaborate with them to push the boundaries of light. With over 100 years of inventions and industry firsts, Lumileds is a global lighting solutions company that helps customers around the world deliver differentiated solutions to gain and maintain a competitive edge. As the inventor of Xenon technology, a pioneer in halogen lighting and the leader in high performance LEDs, Lumileds builds innovation, quality and reliability into its technology, products and every customer engagement. Together with its customers, Lumileds is making the world better, safer, more beautiful—with light.

To learn more about our lighting solutions, visit lumileds.com.

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