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LED Lighting Technolo

International Winning Appr

Calibration and Quality Control of High-Quality Multi-Color LED Lighting Solutions

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Introduction

The LED Revolution in Technical Lighting
LEDs have taken over a larger portion of the technical lighting applications much faster than forecasted some years ago. Many experts predicted LEDs to be the major light sources of the actual decade. However, another group of lighting professionals reminded the lighting industry persistently of the risks of using LEDs in terms of reliability, tolerances in mass production as well as costs.

One major reason for the triumph of the LEDs in technical and consumer lighting definitely was the market demand on cool looking LED applications as well as the designers' preference for the "new" light sources enabling complete new designs regarding geometry as well as color and color dynamics.

Actual Situation

Actually, we have to face the situation that, despite the not negligible amount of drawbacks in the use of LEDs in professional lighting applications, they succeeded in playing a determinative role in many, many systems.

To ensure a high system quality which benefits from the also undenied advantages LEDs can contribute to an optics design project, some additional actions have to be taken - actions that have not been necessary for the development and production of illumination systems using conventional light sources.

In addition to the increased costs for LED driven solutions, the lighting system manufacturers have to face an increased effort for calibrations and quality control measures.

Scope

This paper aims at giving an insight into the state of the art approaches needed to create complex and professional technical lighting applications based on LEDs running properly from a photometric and colorimetric point of view.

The standard way of LEDs to produce light delivers a narrow band spectral distribution which leads to fairly high saturated colors. This fact can be seen as advantage and disadvantage simultaneously. For a wide variety of colored lighting applications LEDs produce exactly the spectrum and color needed for the referring application. Many examples can be found in the signal lighting market, e.g. for traffic lights, railway signalling or airfield lighting applications.

However, for many general lighting as well as technical lighting applications white light is needed. Today the LED suppliers deliver a large choice of white LEDs based on different technologies to produce white light.

One straightforward way to distinguish between the different ways to produce white light with LEDs is to distinguish between LEDs that are able to change their spectral distribution and the others that are not.

Single LED chip systems delivering a more or less constant spectral distribution of white light are not in the focus of this paper.

When talking about high grade applications like medical lighting or architectural mood lighting, the users are interested in the capabilities of multi-chip and thus multi-colored LEDs which enable a dynamic change of the spectral distribution during operation. Due to the multi-chip architecture of the LEDs the spatial mixture of the different colors coming from the different chips gains a much higher importance and thus the measurement and control of color homogeneity.

LEDs suffer considerably from tolerances in their flux per current ratio as well as from tolerances in their spectral behaviour. By using, for example, a multi-color 4 chip LED delivering 4 colors from 4 different chips the tolerances of all 4 chips result in the final tolerances in total flux, luminous intensity and spectral distribution.

The need of an appropriate color mixture of the colors coming from the different chips on the multi-chip LED was mentioned earlier. However, the challenge in most of the systems is even higher. Despite the fact that modern high power LEDs produce more and more luminous output, a larger number of LEDs is still needed to produce sufficient luminous output for technical illumination applications. But again, each of these LEDs contributes its own tolerances to the overall system. Medical lighting systems, for example, may need only a few or up to 50 multi-chip LEDs to create a color alterable illuminance of up to a maximum value of approximately 160 klux.

It is obvious that this approach cannot lead to reliable products without an adjustment or calibration process!.

Demands on the Calibration

The calibration has to be done reliably and in a very short time period to be able to do the process inline of the production without causing any delays in the production cycle time.

The very short time available for the test or calibration process respectively contradicts rather often the needs for a proper heating of the sources to ensure a close to reality result in comparison to the later application.

Measurements on LEDs done in a few milli-seconds don't represent the LEDs behaviour reliably enough. Either a heating period during the test procedure in the test stand or a pre-heating has to be done.

Heating in the test device leads to an increase of the cycle time. Heating in a pre-heating location leads to a higher manipulation and technical complexity and thus to higher costs. Anyway, the sources have to have the temperature typical for their application in order to be able to carry out a reliable and accurate color calibration. Correction factors and compensation models tend to be inaccurate and may fail.

High-grade LED driven products, e.g. in medical lighting, even have to be calibrated in numerous system temperature conditions. Furthermore, if the system is able to be driven at different operating points in terms of correlated color temperature, additional CCR modes have to be calibrated to ensure a high color quality over a large temperature range. The non-linearity of the LED sources makes this even more demanding.

A further difficulty in the calibration of variable LED lighting solutions is the change of the color due the bespoken temperature but also to different LED currents. PWM driven sources suffer less, CW operated sources more from the spectral shift due to the forward current.

Without talking about CRI optimization only the already mentioned issues temperature and CCR lead to a rather large matrix of calibration points and thus to a few tens of calibrations necessary for each single unit. A quick but reliable calibration method is indispensable to assure a high product quality economically.

Equipment

Color

Typically, two main measurement values have to be tested or calibrated on a lighting or illumination system:

The luminance, illuminance or luminous intensity distribution created by the system as well as the spectral distribution and all its appendant measurands like color coordinates, color rendering indices, correlated color temperature and some more.

State of the art spectrometric measurement systems combined with sophisticated algorithms enable the quick and precise measurement and calibration of systems consisting of a number of multi-chip LEDs.

Traditional colorimeters based on an integral measurement of the tristimulus values with a photo-diode-filter-combination suffer considerably from their inaccuracy in their spectral responsitivity. They are not useful to fulfil the requirements on LED testing. The assessment of color rendering values is even impossible without knowledge of the spectral distribution.

When using spectrometers, scanning and non-scanning systems can be applied. Over the last decade non-scanning CCD- or diode-array spectrometer systems have made it reliable and accurate enough to be used in test and calibration machines for high end illumination products. The non-scanning array systems deliver a time benefit additionally.

Fibre optic setups enable ingenious test stand designs with small footprint. The use of fibre bundles ending at different positions in a testing setup expands the test stand to be a multi-point or more or less spatially resolving spectral measurement device. By enhancing the system with one or multiple fibre multiplexers, an analysis distinguishing between the different measurements points can be performed and thus color homogeneity can be measured with very high spectral accuracy.

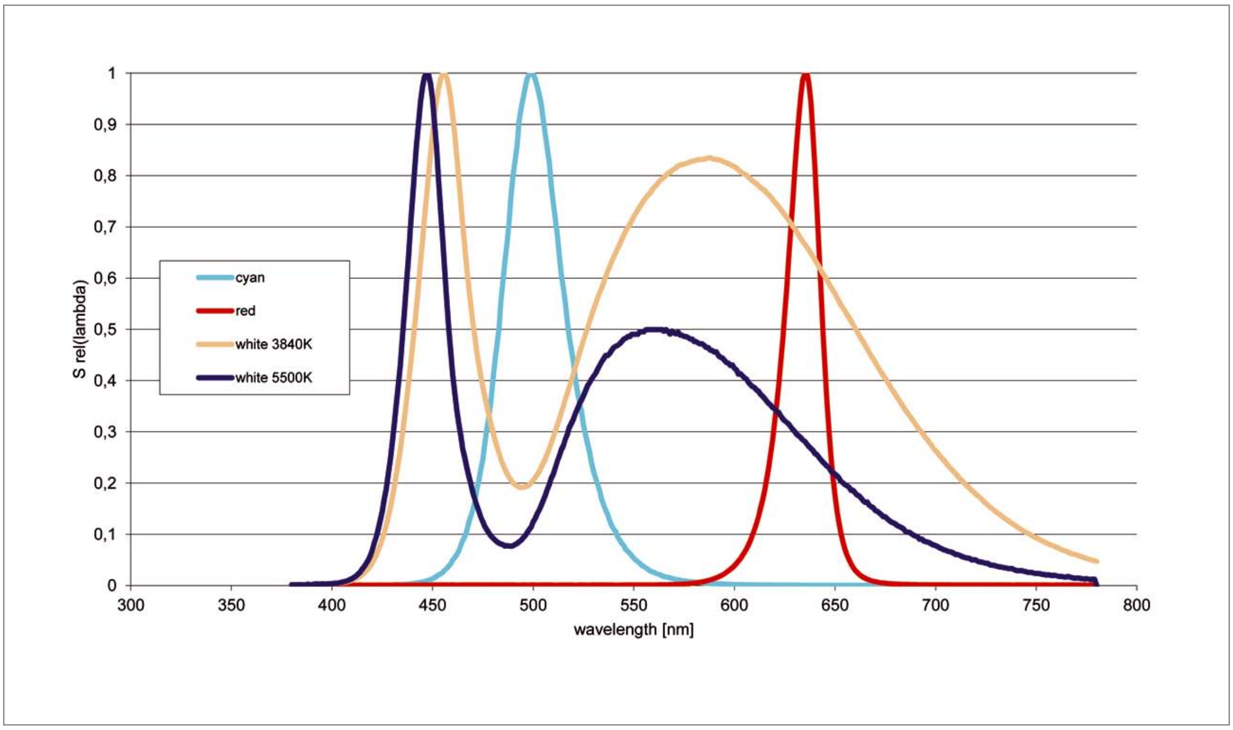
Using a polyspectral imaging photometer system delivers a vastly better spatial resolution but suffers from the inaccuracy of the filters as well as from extended cycle times. And again, CRI testing needs the spectral information without alternative. The analysis of relative color homogeneity can be performed by using the poly-spectral imaging photometer quite well.

Specific values like correlated color temperature, color coordinates or color rendition indices, which affect each other sometimes in a unter-productive way, can be adjusted automatically, inline, reproducibly and reliably by using fast measuring spectrometers combined with sophisticated color calibration algorithms.

Flux and Illumination

In addition to the color calibration the quality control of the photometric output like peak illuminance, illumination distribution or total flux can nowadays be performed by using camera based photometric measurement systems easily.

Figure 1:
Base spectra of different LEDs



Traditional approaches of using an integrating sphere are still well suitable for measuring the total flux of small sources. When speaking about testing complete systems or luminaires, other methods should be used.

The standard way of measuring illumination or luminous intensity distributions is to perform a point by point measurement by using a standard photometer, quite often mounted on an xy-stage or on a classical goniometer.

The goniometer approach delivers quite good results but needs a fairly long measurement time.

The use of imaging photometers based on high-end digital imaging systems enables the measurement of illumination or luminous intensity distributions in a very short time with a spatial resolution unequalled by the goniometric approach.

To derive the metrology results the lighting systems illuminate a high reflecting lambertian plane and the imaging photometer captures the illumination distribution on that plane. Properly calibrated and in knowledge of the geometrical setup the test system delivers the illumination or luminous intensity distribution in less than a second with a very high spatial resolution.

Due to the photometric calibration the total flux in the scenery or also partial flux values can be derived easily with the metrology software. Beyond that, arbitrary geometrical characteristics of the light distributions can be proved easily and quickly. Examples are different field diameters in medical lighting applications, quality assessment of circularity or ellipticity of illumination distributions in entertainment or general lighting or the sharpness of cut-off regions in the light distribution.

The imaging photometer approach leads to a profound and valuable characterisation or testing of illumination systems in a very short time. Another advantage of using imaging photometers in production control and calibration is the image of the distribution that ensures a transparent and demonstrable documentation of the product condition before delivery.

Dependent on the requirements either the colorimetric or the photometric measurands have to be tested or calibrated. However, nowadays high-end LED illumination solutions mostly necessitate both, color and flux calibration. Based on a compound software approach this can be done fast and easily with the described equipment.

Calibration Methods

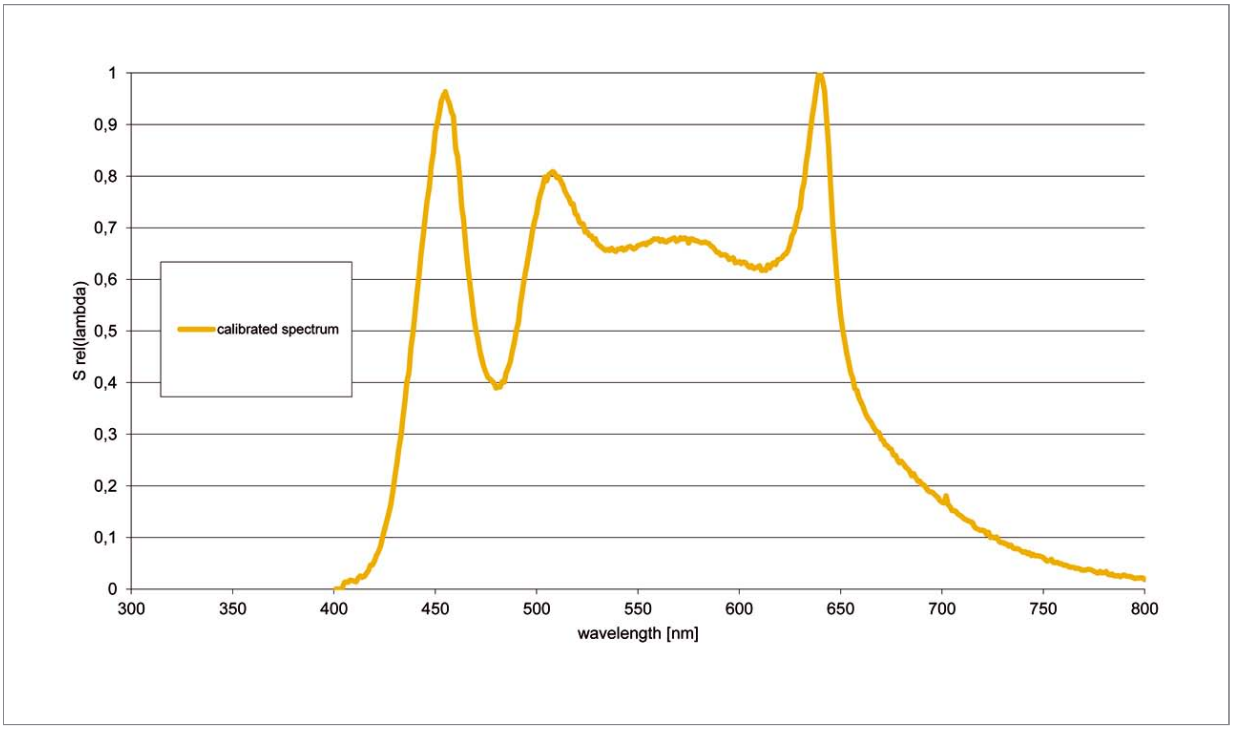
Different methods can be used to realise a quick but precise adjustment of the colorimetric and photometric behaviour of poly-spectral LED lighting solutions. Dependent on the number of different LEDs, sometimes RGB (red, green and blue), sometimes RGBW (red, green, blue and white), the degrees of freedom vary.

The following method describes the color calibration of a “white light” LED illumination system based on four LED colors:

- Warm white, CCR 3840 Kelvin
- Cool white, CCR 5500 Kelvin
- Cyan
- Red

This combination was chosen to be able to adjust the correlated color temperature of the resulting white light in a quite large region. Besides the CCR, the color rendering index is of very high importance in this example.

Figure 2: Resulting calibrated spectrum



For the design of display or signal lighting, CRI typically plays no role in color adjustment. In the case of sophisticated illumination solutions, for example in medical or movie lighting, CRI is of high importance.

The described combination with two different whites and a cyan component fills up the 500 nm gap of a single white LED pretty well. The red component delivers the balancing for optimising the CRIs and helps particularly to improve the R9. Closing this gap is essential to reach fairly high CRI values.

Adjusting color with these four LEDs is nothing more than using different linear combinations of the four LED spectra. Every single color delivers its own CIE1931 tristimulus values X, Y, Z and thus its own color coordinates x and y.

At least two ways can be used now to adjust the desired color:

- A closed loop iterative algorithm can bring the mixed color to the target value in an unknown number of loops.
- Based on the single spectral distributions of the LEDs and the desired color coordinate a set of linear equations can be set up and solved.

The second approach is more straightforward and offers much more control over the time needed in the production process.

All LED base colors have their own tristimulus values X, Y, Z. The tristimulus values of the resulting mixture of the different colors can be described by a linear combination of the single tristimuli.

Now, an equation to describe the target color coordinates based on the single tristimuli can be set up. In this particular case, with four base spectra, two weighting factors are needed to find a solution for the target color coordinates and the other two can still be chosen arbitrarily.

In other words, we get a two dimensional "array" of solutions with two remaining arbitrarily selectable weighting factors.

However, color coordinates are not the only targets to hit normally. Many illumination applications need to achieve a rather small color distance dC to the Planckian or black body curve in in the CIE1931 x, y color chart as well as an optimum in the color rendering index Ra. Some applications, like for example medical lighting systems, furthermore demand a very high R9 value. To optimize dC and CRI the calibration algorithm can find the optimum values for the two still selectable weighting factors.

Finally, this approach adjusts the weighting of the four base colors in a way that the resulting mixture of the colors meets exactly the desired color coordinates with an additional optimisation of dC and CRI in one calculation step without the need to perform multiple time consuming measurements in an iterative loop.

The total flux or peak illuminance respectively can now be adjusted by a proportional scaling of all weighting factors together easily.

Due to the non-linear behaviour of the LEDs dependent on its forward current this approach can produce small deviations in hitting the target chromaticity coordinates.
A second spectrometric measurement after the calibration algorithm is finished discloses these eventual deviations right away. The same procedure can be done once more with the already found weighting factors used as the starting values of the calibration algorithm, if necessary.

Now, the non-linear behaviour doesn't affect the result significantly because the corrections on the weighting factors are quite small in this second step. The lighting system is calibrated and the weighting factors for the different colors are stored in the LED electronics.

In this example the following resulting spectral distribution was adjusted by the calibration algorithm:

The target chromaticity coordinates were hit almost exactly due to the used algorithm. The other measurands were hit pretty close with the first adjusting step to:

Target peak illuminance:	38.429 lux
Adjusted peak illuminance:	38.124 lux
Target CCT:	4500 Kelvin
Adjusted CCT:	4639 Kelvin
Max dC to Planck:	0.025
Adjusted dC to Planck:	0.00114
Min target CRI Ra:	98
Adjusted CRI Ra:	99.016
Min target CRI R9:	98
Adjusted CRI R9:	99.39

If desired, a second loop of the adjustment or calibration algorithm would bring the values even closer. However, only one calibration step brings the values almost exactly to target!

More sophisticated systems with multiple operating points on many different illumination levels as well as many different correlated color temperature modes typically need to have a large array of calibration value sets to ensure the best product quality in the different modes. It depends on the system and the linearity of the LED sources how many interim values between real calibrated values can be interpolated by a luminaire intrinsic algorithm.

The described calibration of poly-spectral LED lighting systems ensures a high color quality of the products at the beginning of their life time. However, as a result of the well-known degradation of LED sources over their life time the desired chromaticity coordinates will differ more and more gradually. This is even more critical as the different base colors show a different degree of degradation over the years. In some applications this effect is well-known and the LED electronics is compensating this effect based on the total operating time of the LEDs.

In modern systems with a high demand on color quality and stability an additional simple color detector is included in the lighting system electronics. After the calibration is finished and the weighting factors are written to the luminaire electronics the color detector value is stored also. The simple color detector would never be able to do the complete calibration but it's good enough to detect the degradation of the single LEDs over life time and to correct the different weighting factors step by step correspondingly.

Conclusion and Discussion

LEDs have revolutionised part of the modern illumination industry and enabled a series of new features and applications.

On the other hand LEDs and as a consequence the higher demands on LED solutions made a new kind of lighting products calibration and new approaches on lighting quality control indispensable.

This paper describes some reasons why poly-spectral LED lighting systems need to be calibrated as well as some technical solutions to achieve the desired product quality for a long product life time.

The described equipment and methods proved their capability and efficiency in various applications of modern LED lighting systems already. ■

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Lector: Uta Vocke

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