Light & Engineering
Vol. 28, No. 1, pp. 90–98, 2020
https://doi.org/10.33383/2019-043
Svetotekhnika #5, 2019, pp. 13–19

REALIZATION OF A LABORATORY TUNEABLE COLOUR LIGHT SOURCE

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ABSTRACT

A spectrally tuneable colour light source (TCLS) has been designed and constructed at Physikalisch-Technische Bundesanstalt (PTB), Germany. It consists of an integrating sphere with 24 LEDs which are driven by a computer-controlled power supply. It is intended for producing any visible spectral distribution and to mimic various light sources for use in laboratories as a calibration source. With the help of an integrated spectrometer, a closed loop operation was introduced to improve the performance of the TCLS and to spectrally stabilize its output spectrum. Before practical realization of the TCLS a series of simulations have been made to predict its performance and capability with a number of different target spectrums. During the practical implementation we have encountered difficulties, namely optimization of the output spectrum, dependency of LED spectra on the electric current through the LED and temperature of the LED, non-linearity of LED's luminous flux with respect to electric current through the LED and some difficulties with small synthesis coefficient values, which were all successfully solved.

Keywords: LED, tuneable colour light source, spectral power distribution, LabVIEW

1. INTRODUCTION

Tuneable colour light sources (TCLS) are suitable for different purposes and cannot only be used for general lighting purpose but also in laboratories for calibrations. These TCLS are actually multichannel light sources today mostly based on a set of different light emitting diodes (LEDs) which are able to mimic different spectral power distributions (SPD). Some tuneable light sources with different number of LEDs and with adaptable spectrum are already commercially available for applications in lighting, chemistry research and entertainment. The ones for use in general lighting are often only capable to produce white light with different correlated colour temperature [1] and comprise two to four different LEDs. Multichannel LED sources are also used for different chemical tests and measurements. They usually comprise four to eight different monochromatic LEDs with peak wavelengths distributed across the visual part of the spectrum. For stage lighting also multichannel LED light sources (spot lights) are used with single colour LEDs and white light LEDs. Compared with tuneable colour light source for laboratory use and the calibration of photometric instruments, such devices often have a lower number of different LEDs and they do not include spectrometers for real time measurements of the output spectrum. Measurement of output spectrum and "closed loop" operation provides the ability to regulate and stabilize the TCLS calibration source output spectrum, which is a critical property for a source used for calibrations. The ideal TCLS calibration source should be able to simulate any wanted light source with defined spectrum, which then can be used for calibrations of photometric measuring equipment.

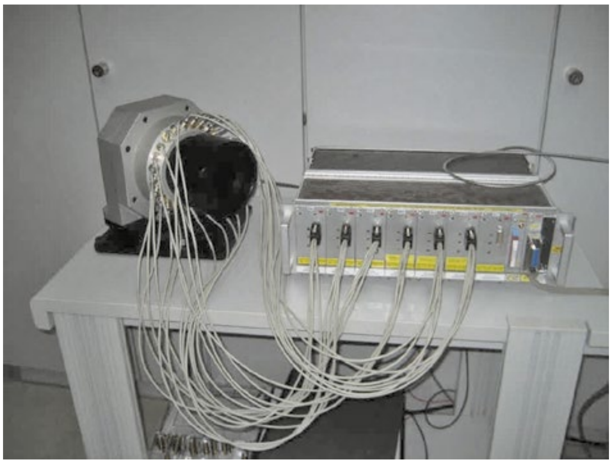

Fig. 1. Tuneable colour light source for calibration purpose: on the left is the sphere with LEDs around the output port; on the right is the 24 channel DC source of power

It is important that the TCLS calibration source produces various SPDs with defined photometric or colorimetric parameters, namely luminance, correlated colour temperature (CCT), colour coordinates (*x, y*) or colour rendering index (*CRI*). Realization of illuminants with different SPDs by just one light source is making calibration of equipment of different SPDs much easier and more economical. Beside realization of SPDs of real light sources TCLS calibration sources offers also the ability to realize only theoretically defined illuminants.

The TCLS calibration source based on an integration sphere with 24 entry ports for LEDs has been developed at PTB, Germany. The built TCLS calibration source is mainly intended for calibration of different instruments and measuring equipment at various spectra [2]. In this paper we describe the control program we use to control the TCLS calibration source and problems that occurred during development. Most problems resulted from the practical application of the developed optimization method and the properties of real LEDs, which do not change linearly over time and electric current. The paper also shows the performance of the developed TCLS calibration source.

2. CONTROL OF OUTPUT SPECTRUM

The idea of the TCLS calibration source based on larger number of LEDs used to produce any wanted spectrum. The basis of the TCLS calibration source is an integrating sphere equipped with many ports for multiple LEDs installed in a circle around the output port. As the LEDs are baffled and only illuminate the back of the sphere, no direct light can leave the sphere, Fig. 1. LEDs are connected to the multi-channel DC power supply where each individual LED or group of identical LEDs is connected to one of the channels. The DC power supply is connected to the controlling personal computer (PC) via GPIB bus, which enables to control each channel's current separately. The circle of LEDs around the output port of the sphere ends with a spectrometer fibre input port. Also the used spectrometer is connected to the controlling PC via USB. The TCLS calibration source is controlled with a program written in LabVIEW™ environment.

Since the TCLS calibration source is intended as a luminance source with an adjustable spectrum, it is very important that the current of each LED can be set individually. An internal output coefficient K_i, where i is the number of specific LED, is used within the control program to describe the individual settings, which is based on the ratio of the luminous flux at a given current setting with respect to the luminous flux of the LED at its nominal electrical current. The value of K_i is in a range from 0 to 1. In this way, the contribution of each LED to the overall light output of the TCLS calibration source can be described.

The procedure to calculate the needed 24 coefficients K_i for the wanted synthesized spectrum consists of a few steps. The goal of the program is to adapt the output spectrum, which is measured, as close to the target spectrum as possible. In a first step, the wanted spectrum is loaded into the program as "target" spectrum and program tries to find a "best fit" with the premeasured spectra of the LEDs which are installed in the TCLS calibration source. Because the total light output of the TCLS calibration source should be adjustable to be adapted to the wanted luminance without changing in the shape of the spectrum, the target spectrum is normalized to 1. The control program provides the possibility to set the number of LEDs to be used for the synthesis of target spectrum and its nominal currents. After that, the control program starts measuring the spectra of the used LEDs. With the known target spectrum and individual premeasured spectra of the single LEDs, synthesis coefficients are calculated according to shape a synthesized spectrum as close to the target spectrum as possible.

To be able to produce a light source with any wanted spectrum, the TCLS calibration source was equipped with 22 monochromatic LEDs and two

Table 1. Peak WL (nm) and Relative Power of the Chosen 24 LEDs

LED	Peak WL /nm	Relative power	LED	Peak WL /nm	Relative power
1	380	0,042	13	599	0,116
2	388	0,361	14	628	0,648
3	405	0,463	15	654	0,069
4	424	0,900	16	666	0,099
5	431	0,943	17	692	0,086
6	456	0,645	18	707	0,071
7	466	1	19	721	0,058
8	492	0,500	20	739	0,044
9	498	0,341	21	762	0,023
10	513	0,213	22	774	0,018
11	531	0,131	23 (WW)	572	0.0339
12	590	0,390	24 (CW)	451	0.1516

additional white LEDs (warm white LED and cool white LED), whose spectra can be seen in Fig. 2. The LEDs were chosen so that their SPDs are evenly distributed throughout the whole visible part of the light spectrum from 380 nm to 780 nm. Such distribution allows to synthesizing a continuous output spectrum.

The warm white (WW) and cold white (CW) LEDs were added to the set because of a lack of LEDs with appropriate peak wavelength (WL) in the spectral range around 550 nm. The peak wavelengths and relative powers of corresponding LEDs are shown in Table 1 where the white LEDs are represented by the 23rd and 24th LED. Relative outputs (relative powers) at peak wavelength in Table 1 were used for better understanding of different power outputs of LEDs. Spectra of all LEDs are scaled according to the one with the maximum power output. Since LEDs with peak WL from 650 to 780 nm have really low output compared to other LEDs, the total luminous flux output of the TCLS calibration source may be very low for some synthesized spectra with large component of light with longer wavelengths (red part of a visible spectrum).

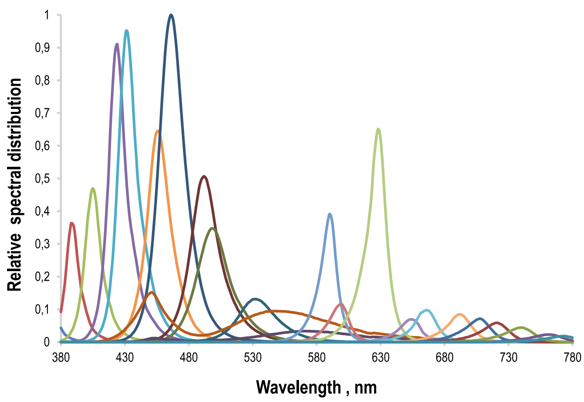

Fig. 2. Spectra of the LEDs set used in the TCLS calibration source, with 22 monochromatic LEDs and 2 white LEDs as measured by the control program of TCLS at their nominal current; spectra are normalized to the spectrum of the most powerful LED

3. OPTIMIZATION METHOD

The optimization process is, in this case, an automated procedure to control the chosen set of LEDs in order to find the ideal combination of LEDs and their respective driving currents to synthesize requested target spectra. A common (synthesized) spectrum of all 24 LEDs is optimized so that the output spectrum at the port of the sphere is as close to the target spectrum as possible. The optimization criterion is based on a sum of the squared differences between the spectrum of the TCLS calibration source and the target spectrum at a single wavelength (with 1 nm step) that needs to be minimized (least squares optimization). The so-called synthesis error can be described by the equation

$$S_{err} = \int \left(b(\lambda) - a(\lambda)\right)^2 d\lambda, \qquad (1)$$

where $a(\lambda)$ is the measured spectrum of the TCLS calibration source and $b(\lambda)$ is the target spectrum. The value of S_{err} can also give us an estimation of the quality of the spectral match of the TCLS calibration source output spectrum with respect to the target spectral distribution.

There are a lot of research papers related to the topic of tuneable colour light sources based on LEDs and how to fit the synthesized spectrum as close to the target spectrum as possible. To satisfy mentioned condition two different approaches are possible, namely through a trial or through an approximation. Fryc et al. [3] proposed a tuneable light source using LEDs where the optimization (fit) of the spectrum was done with a simple but slow iterative procedure, whereas Wu et al. [4] introduced the pruning process where optimization is done by removing LEDs to find an optimal set of LEDs. Most of the methods in papers are based on Gaussian optimization method, which is used to solve non-linear least squares problems with minimizing the sum of squared function values. In our case, we also use Gaussian optimization to minimize the sum of squared differences between the measured synthesized spectrum of the TCLS calibration source and the target spectrum, as it gives the smallest difference between these two spectra. Synthesis coefficients (K_i), which are calculated during the optimization procedure, together form a synthesized spectrum that comes closest to the target spectrum. Unfortunately, basic Gaussian optimization method can return results where some values of K_i become negative. As the synthesis coefficients K_i represent the luminous flux of each LED, where the luminous flux cannot be negative, a synthesized output spectrum cannot be realized with negative coefficients. Therefore, what is needed is a method that takes into account other constraints besides minimizing the sum of the squared differences, namely that calculated values of all coefficients K_i to be positive or equal zero. Lawson and Hanson [5] described a procedure of a non-negative least squares (NNLS) optimization method, which is proved to be an optimal solution for a non-negative problem with certain inequality constrains. Bro and De Jong [6] proposed a fast non-negativity-constrained least-squares algorithm, which is based on the standard NNLS algorithm in [5], whereas Cantarella and Piatek [7] announced a freely available *C* implementation of sparse constrained least-squares problem.

Due to the fact that we can only accept positive values (or values equal to zero) as a suitable solution of Gauss optimization method, we tested the NNLS method which does take into account constrain of the positive (or zero) synthesis coefficient values. Firstly, we tested number of different methods as well as the NNLS method in simulations where we used actual measured spectra of LEDs from the TCLS calibration source. As NNLS method gave the best results for all tested target spectra, we decided to implement it in the LabVIEW™ environment used to control the TCLS calibration source.

The optimization method based on NNLS is defined by statement:

- Minimize $||Ax–b||$, subject to $x \geq 0$

where A is the $m \times n$ matrix with $m \geq n$; b is the m element data vector and x is the n element solution vector; A solution for the equation $Ax \approx b$ must be found, where $x \geq 0$. Entries of the matrix A are the components of the sampled SPDs of the measured LEDs, where n is the number of LEDs and $m=401$ is the size of the sampled SPD vector with 1 nm step in range from 380 nm to 780 nm. The target spectrum is sampled in a vector b with the same size $m=401$ as matrix A.

Lawson and Hanson in [5] described the algorithm in nine steps. The procedure starts with setting all elements of x to zero, creating set Z, containing all indices, and an empty set P. In the main loop the gradient vector w is calculated with the current value of x using the equation

$$w = A^T\left(b - Ax\right). \tag{2}$$

If Z is empty or if all elements of w with indices in Z have values ≤ 0, the solution is found and the procedure terminates. Otherwise in the next step the maximum element of w is moved from set Z to P. If any of the elements have negative values, only a fraction of Z can be accepted as a trial solution. Therefore, in the next step one need to find an index q such that the expression

$$\frac{x_q}{\left(x_q - z_q\right)} \tag{3}$$

is the minimum of all such expressions for negative elements of Z. For this q call the expression for α so, that the linear sum can be calculated (4).

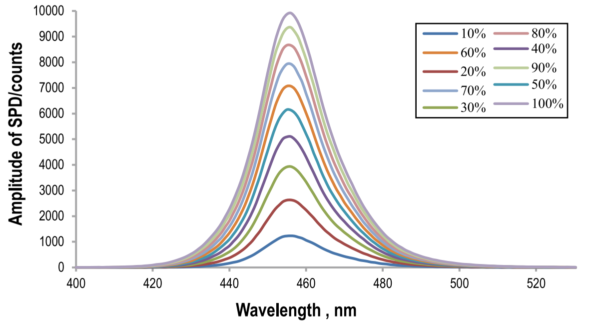

Fig. 3. Dependence of amplitude of the LEDs spectrum for increasing currents. Legend represents the percentage of the nominal current, which was used to measure SPD in the same colour

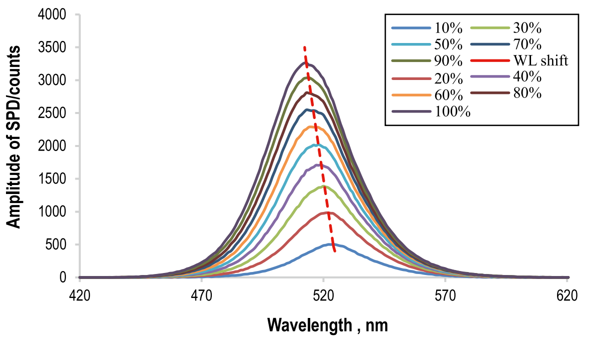

Fig. 4. Example of dependency of LED spectrum amplitude and peak wavelength on increasing current; legend shows the percentage of the nominal current for each SPD and dashed red line marks the shift of peak wavelength

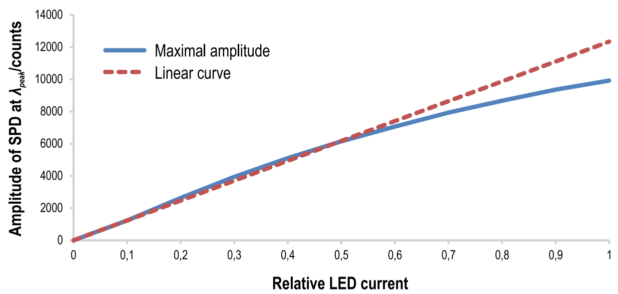

Fig. 5. Amplitude of the LED SPD of at different relative currents with respect to the nominal current; the dotted line shows a linear extrapolation of the initial linear behaviour below 10 % of the nominal LED current

$$x = x + \alpha\left(z - x\right). \quad (4)$$

In the final step all indices for which the corresponding elements of x is zero, are moved from set P to Z. These will include x_q, but may also include other elements as well. When the procedure converges, the set P provides a vector of the synthesis coefficients. The procedure is also described in more details in [8].

4. PROBLEMS WITH REALIZATION OF TCLS IN PRACTICE

The main question that arises with the realization of the TCLS calibration source and in particular the optimization procedure in practice is, how calculated luminous flux percentages defined by optimization coefficients K_i can be converted to the required electrical current through the LEDs. The implemented NNLS method uses measured spectra of LEDs for calculation of K_i. Each K_i represents the required amount of luminous flux of one particular LED at its nominal current. Unfortunately, the luminous flux is mostly not linearly dependent on the electrical current through the LED, so K_i cannot be directly used to calculate the required LED current from its nominal one. To calculate the LEDs current properly, the dependence of LED's SPD for increasing driving currents needs to be taken into account. One example of such dependence is given in Fig. 3.

The changes of the LEDs electric current will also affect the p-n junction temperature, which consequently leads to a change in LEDs SPD. Such a change of the SPD will shift the LEDs peak wavelength depending on the individual current and hence, will also change the colour of the emitted light. However, as only a very small peak wavelength shifts of the LEDs used in TCLS calibration source were detected, a procedure that takes such shifts into account was not integrated in our optimization procedure. Instead, an additional feedback control procedure was integrated in the LabVIEW™ program, which, apart from maintaining a stable output of the TCLS calibration source, is also capable to eliminate the relatively small impact of LEDs wavelength shift on final output spectrum. In future, if the used LEDs will be replaced with LEDs providing higher output power which also causes larger wavelength shifts, a procedure within the algorithm for taking such shifts into account will be necessary. An example of LED's peak wavelength shift can be seen in Fig. 4.

To determine the dependency of the LED luminous flux on the electric current more than one measurement of the LED SPD need to be done. The control program of the TCLS calibration source, therefore, uses 10 measurements of each LED at different currents from 10 % of the nominal current (I_{max}) up to 100 % of I_{max} in 10 %-steps. The program starts with the first LED, whose current takes up a preset value of 10 % of I_{max}, and proceeds with the second LED and then the third LED and so forth. After the last LED in the set measurement, the current increases by the value preset of 10 %. The program carries out nine increases of currents and therefore 10 measurements of SPDs of each LED.

If we use the amplitude of the SPD at the peak wavelength as a measure of the LED luminous flux, its dependence on the current through the LED can be shown in a graph similar to the one given in Fig. 5. To include this dependency into the control procedure of TCLS calibration source it needs to be expressed by a mathematical expression. It was found that the current – flux dependency can be approximated by a polynomial curve. In most cases a 3rd order polynomial curve represents the measured dependency with sufficient accuracy.

Using the determined dependence between the luminous flux and the electrical current of the LED, as shown in Fig. 5, the required electric current for the required luminous flux for each LED can be calculated from synthesis coefficients (K_i) previously calculated by the optimization procedure for the target spectrum. However, before correcting the synthesis coefficients K_i it must be checked whether the values of K_i are large enough to ensure the optimal total luminous flux output of the TCLS calibration source. The synthesis coefficients K_i of each LED represent the required LED luminous flux, where the coefficient equals one for the luminous flux at a nominal electrical current. If the value of coefficient is too small, e.g. smaller than 0.05 to 0.1, the LED will typically not turn on due to low forward voltage. To prevent such small values and to ensure the optimal total luminance of the output port of the TCLS calibration source, all LEDs are normalised according to the LED with the largest required luminous flux value to achieve the target spectral distribution. The electric current for the LED with the largest synthesis coefficient K_i is set to its nominal electric current and the currents through the other LEDs are scaled accordingly. At the same time, the target spectral distribution is also scaled by the same value to be able to compare target and output spectrum. If some of synthesis coefficients K_i become smaller than required to turn on the respective LEDs, these LEDs are excluded from the set of used LEDs for this particular target spectrum and the optimization procedure has to be started again to obtain new "best fit" without the excluded LEDs.

Because of temperature fluctuations and aging, the output of the TCLS calibration source, namely the spectra distribution at the sphere output port as well as the SPDs of the individual LEDs, can change with time. In order to diminish the mentioned impacts, an additional regulation procedure was added to the control program. It is a simple iterative optimization process, which tries to minimize the synthesis error S_{err} by small changes in the electrical current through each LED. With this procedure the output of the TCLS calibration source stays stable and it turns out that in some cases S_{err} get even slightly better (smaller). This is mainly a result of the possibility to perform a closed loop feedback control using the implemented spectrometer, which is the major advantage compared to other commercial tuneable colour light sources. In a first step, this additional feedback procedure increases the current through the LEDs one by one for a set value in between 1 % to 5 % of the nominal current. The size of the step can be set in a control program. After the current of a single LED is increased, the output spectrum is measured by the integrated spectrometer and the synthesis error S_{err} is recalculated. If the obtained value of S_{err} is improved, the current change for this LED is kept for future. If value of S_{err} worsened, the current is set to its original value. Then the feedback procedure continues with the next LED. After all LEDs are checked in this way, the feedback procedure starts again with the first LED to try to improve the value of S_{err}. If an increase of the current did not result in better S_{err} in previous round, the current of the LEDs will be decreased by a set value in the next feedback loop. In this way, slight changes of the LED currents in both directions are put into effect to improve the match between the spectral power distribution of the TCLS calibration source and the target spectrum and to keep the TCLS calibration source stable even if the operating conditions and performance of single LEDs of the TCLS calibration source are slightly changing.

Hence, the control program of the developed TCLS calibration source is composed of three sub-routines. After starting the control program, the target spectrum is loaded and the rated currents of installed LEDs are queried. The first subroutine determines the characteristic of the luminous flux with respect to the electrical current of all LEDs. It starts at 10 % of the rated current and continues in 10 % steps up to the 100 % level. After all LED are measured the optimization procedure of the second subroutine starts and calculates synthesis coefficients

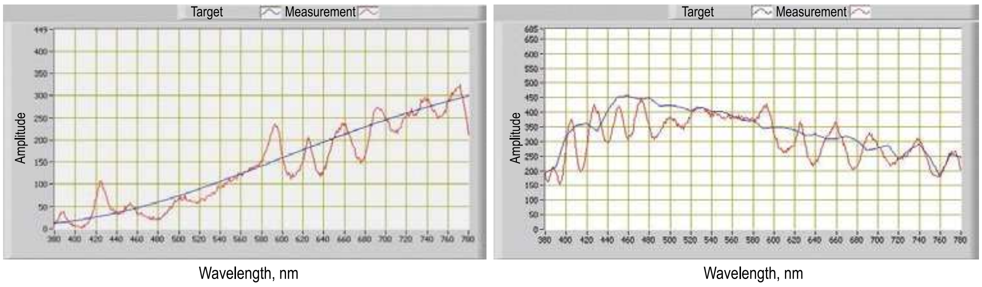

Fig. 6. Target spectrum (blue) and optimized output spectrum (red) for synthesis of Illuminant A (left) and D (right) spectra

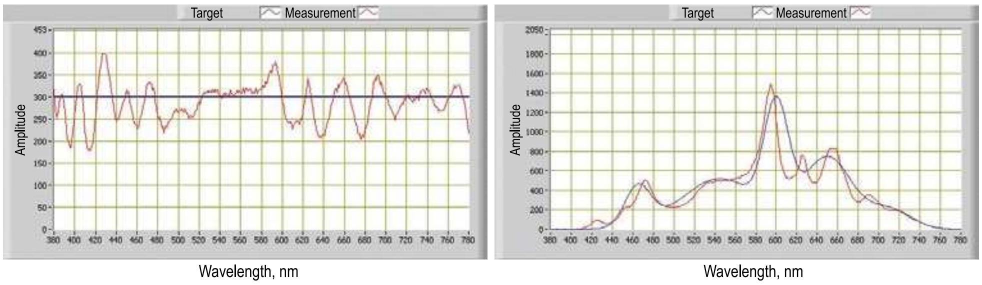

Fig. 7. Target spectrum (blue) and optimized output spectrum (red) for synthesis of EE05 (left) and OLED (right) spectra

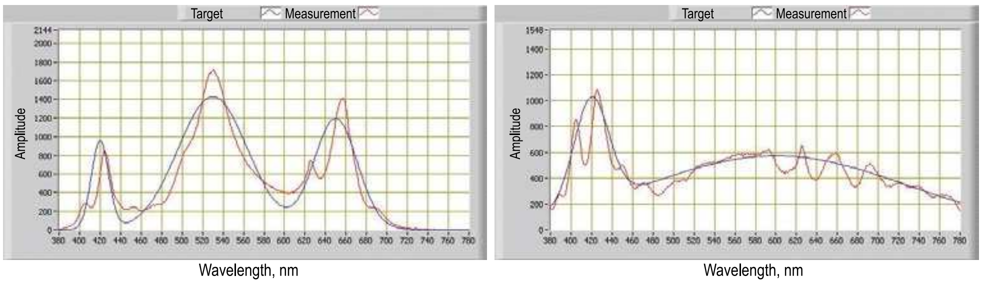

Fig. 8. Target spectrum (blue) and optimized output spectrum (red) for synthesis of RGB (left) and WLED (right) spectra

K_i (i.e. a measure of the required currents for the LEDs) to synthesize the target spectrum. At the end of the optimization process the calculated synthesis coefficients are increased linearly so that the largest becomes 100 %. This is done to achieve the highest possible luminance at the output port of the TCLS calibration source for the requested target spectrum. At the end of this subroutine the synthesis coefficients are transformed into the required LED's electrical currents using the previously measured luminous flux versus electrical current characteristics. Finally, the power supply channels of the TCLS calibration source are set to proper values and turned on. After a warming up period, needed for stabilization of LEDs output, the third subroutine takes over with the feedback control to continuously measuring the output spectral distribution and trying to improve the match to the target spectrum by slightly changing the current through every single LED as described above.

5. RESULTS

The TCLS calibration source is designed to match any spectral distribution in the restricted interval between 380 nm and 780 nm. The matching of the SPDs generated by multiple LEDs to the target spectrum is realized using the optimization method described in the chapter 3. Due to non-linear LED characteristics, calculated synthesis coefficients must be properly adjusted for the conversion into the required currents through the LEDs. To make this possible through mathematical algorithms, a large number of SPDs measurements for LEDs must be performed, which prolongs the time of the entire process. To improve the start-up time all measured SPDs can be saved and used again later, e.g. for other target spectra. The realized spectral distributions of the TCLS calibration source can be different from the target spectrum distribution due to limitations in the optimization procedure as well as due to limitations by the restricted number of LEDs used in TCLS calibration source, their appropriate peak wavelengths and shifts in their radiometric output due to temperature fluctuations or aging, etc.

If setup properly with the used procedure and with the measured and saved LED's SPDs at different currents, the TCLS calibration source provides practically instantly an optimized output spectral distribution at the output port of the sphere. Due to the spectral feedback control mechanism based on periodic measurement of the output spectrum using a spectrometer, the provided spectrum is kept constant during operation. A major advantage using the implemented spectrometer and periodic real time measurements is the possibility and flexibility to replace one or more of the LEDs in the set without any additional calculations or changes within the LabVIEW^{TM} control program. The whole process, starting from the measurement of SPDs of the installed LEDs until the synthesis and control of the output spectrum is automated.

To show the quality of the synthesized spectra some examples with well-known target spectra are provided. Figs. 6 to 8 show results of the optimization and synthesis of six target spectra, namely CIE standard Illuminant A spectrum, CIE standardized daylight D_{65} spectrum equal energy spectrum (EE05), spectrum of generic OLED, spectrum obtained for RGB-LEDs and a spectrum of white LED (WLED). For these examples the set of LEDs described in chapter 2 was used. All spectra shown were measured with the TCLS integrated spectrometer.

5. CONCLUSION

A TCLS calibration source was designed to explore the possibility and use-ability in photometric laboratories for calibration of different instruments and measuring equipment at various spectra. Beside this main task, the developed TCLS calibration source may also assist research for new CIE standard light sources for calibration. Choosing NNLS method for optimization of the TCLS calibration source output spectrum gave good results and show small difference between target spectrum and TCLS calibration source output spectrum, although the number and types of used LEDs was restricted. Due to the integrated spectrometer and iterative procedure described in chapter 4 it was possible to further improve the match of the output spectrum with respect to the target spectrum. There are still noticeable differences between both spectra, as shown in Figs. 6 to 8, which could be improved in the future by using more LEDs for the next generation TCLS calibration source.

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