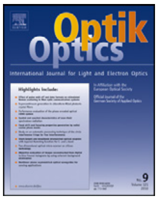
Optik 124 (2013) 644–649

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Accuracy simulation of an LED based spectrophotometer

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ARTICLE INFO

Article history:
Received 26 August 2011
Accepted 27 December 2011

Keywords:
LED based reflectance spectrophotometer
Wavelength
Color measurement

ABSTRACT

In this paper, the achievable accuracy of a reflectance spectrophotometer based on 18 LEDs of different peak wavelengths in the range of 390–710 nm for object illumination is reported. For simulating the accuracy, reflectance spectra of the color target ColorChecker® have been used. By weighting the reflectance spectra of the target with measured relative power distribution spectra of the employed LEDs, simulated spectral reflectance values of the target are obtained. For calculating color values, unique wavelength values must be assigned to the simulated spectral sample values. LEDs can be characterized by several wavelength parameters. It has been shown that, without applying a correction procedure, assigning the centroid-wavelength of the LEDs as color calculation basis delivers the best results. But if a linear correction matrix is introduced, an optimized equidistant wavelength assignment delivers the best results. The mean achievable precision is sufficient to determine color values below $\Delta E_{ab} < 0.3$.

1. Introduction

Light is defined as the visible portion of the spectrum generated by electromagnetic radiation. The wavelength range extends from 380 to 780 nm. The reflectance spectrum of an object's surface is – like a fingerprint – a characteristic feature. It can be directly used to identify an object. Furthermore, spectral data are the basis to determine color values of objects. The accuracy of a color measurement is acceptable if the deviation to a reference is below $\Delta E_{ab} < 1$. For this accuracy, at least 16 spectral sample values (i.e. approx. every 20 nm) in the visible range are required [1]. One way to obtain spectral reflectance data is to illuminate the object with a broadband light source (white light) and to decompose the reflected light by means of diffraction gratings or optical prisms. The wavelength-separated light components are detected subsequently by a CCD sensor or a photo diode array. This method is commonly used and achieves high spectral resolution and accuracy. But the required precision optical components usually lead to high costs.

Another way to obtain spectral reflectance information is to illuminate an object's surface successively with several narrowband light sources of different wavelength in the visible region and to detect the reflectance of each illumination with a single (broadband) light detector (e.g. silicon photo diode). For accurate measurements, the employed light sources should have an infinite small bandwidth. On the other hand, a light source with infinite small bandwidth is not known. Therefore, the achievable measurement accuracy is limited.

Very cost-effective and fairly narrowband light sources exist in the form of light emitting diodes (LED). LEDs are available commercially with diverse peak-wavelengths in the visible range. Therefore, they are a subject of interest for the use as illumination sources in a low cost LED based spectrophotometer.

There are several approaches for LED-based spectrophotometers for the visible region, which are described in literature. In [2] and [3] an absorbance measurement spectrophotometer is described that uses seven LEDs of different colors. A low cost flow-injection analyzes system, that involves only three LEDs of wavelengths 430 nm, 565 nm and 625 nm, is described in [4]. Also in [5] a spectrophotometer with only 3 different LEDs can be found. In [6], a performance simulation of an LED based spectrophotometer for color measurement using eight LEDs of different colors is described. A special spectrophotometer for absorbance measurements in the wavelength range from 530 to 600 nm using LEDs equipped with narrowband interference filters can be found in [7]. All above mentioned approaches suffer from low spectral resolution. Hence, they are not appropriate for accurate colorimetric measurements.

In this paper, an approach for a spectrophotometer is described which is sufficient for colorimetric measurements. 18 LEDs with given peak-wavelengths in the range of 390–710 nm are involved to obtain spectral reflectance values about every 20 nm. The main problems with using LEDs are caused by their bandwidths and disadvantageous spectral curve shapes. This is the main reason for accuracy limitations. The achievable precision of such an LED based spectrophotometer has been simulated for several possible wavelength parameters of the LEDs and several illuminants.

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doi:10.1016/j.ijleo.2012.01.005

Table 1
Parameter for characterizing LEDs.

Parameter	Definition
Peak wavelength	Defines the wavelength of the intensity maximum
Full width half maximum (FWHM)	Defines the difference of the wavelengths for which the intensity falls to 50% of its maximum.
Center wavelength	Defines the mean of the wavelengths of the FWHM
Centroid wavelength	Defines the wavelength at which the half of the integral radiation power is located.
CIE *xy*	Color locus according to the CIE chromaticity diagram (CIE: Commission internationale de l'éclairage)
Dominant wavelength	Defines the matching wavelength, which is perceived by the human eye. The dominant wavelength is calculated from the CIE *xy* color locus.

Furthermore, a simple linear correction method has been applied to improve the performance. The results are presented in this paper.

2. LED characterization

For characterizing the color of LEDs, several parameters are defined. Table 1 gives an overview of the most common parameters. The peak wavelength is the preferred parameter for characterizing the emitted wavelength and is usually given in the data sheets. For illustrating the wavelength-based parameters, a typical LED spectrum with a given peak wavelenght of 645 nm is shown in Fig. 1.

For the spectrometer approach, 18 standard LEDs were purchased by Roithner Lasertechnik (Roithner Lasertechnik GmbH, Vienna, Austria). The relative power distribution spectra of the LEDs were measured with a TRISTAN® spectrophotometer (mut AG, Wedel, Germany). For the measurement, all LEDs were operated at a constant forward current of $I_F = 20$ mA and at a constant temperature of 22 °C. Columns 1 and 2 of Table 2 present the type and the given peak wavelength of the purchased LEDs as stated in the data sheets. From the measured spectra of the LEDs, the parameters presented in the columns 3–9 of Table 2 were calculated. It can be seen that the calculated peak wavelengths (column 3) differ from the given peak wavelengths. This is due to the manufacturing tolerances. An interesting aspect is the fact that the dominant wavelength partially deviates strongly from the given peak wavelength. This means, the perceived color of such LEDs by the human eye may be significantly different in comparison to the color that is perceived by watching the given peak wavelength. A measure of the bandwidth of the LEDs is given by the full width half maximum (FWHM) parameter in column 7. It is obvious that illuminants with FWHM values exceeding some 10 nm cannot be assumed as narrow banded. The CIE *xy* values (column 8 and 9) determine the color locus according to the CIE *xy* chromaticity diagram. The dominant wavelength (column 6) represents the matching wavelength that is perceived by the human eye and is calculated from the CIE *xy* values [8]. The center-wavelength (column 4) and the centroid wavelength (column 5) are alternative wavelength parameters for characterizing LEDs (see definition in Table 1). The values depend on the spectral curve shape of the LEDs.

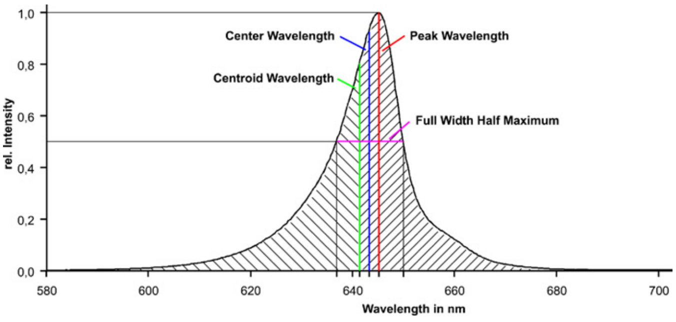

Fig. 1. Typical spectrum of a light emitting diode with 645 nm peak wavelength.

Fig. 2 depicts the measured spectra of the 18 LEDs. The curves in the diagram were scaled so that all spectra represent equal integral power. This explains why in the diagram narrow banded LEDs have a high intensity maximum and vice versa. It can be seen that the spectra are overlapping extensively. Furthermore, the diagram shows that every LED has an individual spectral curve shape.

3. Spectrophotometer simulation

For the simulation of the LED-based spectrophotometer, reflectance spectra of the color target ColorChecker® (X-Rite, Inc.) have been utilized. The target consists of 24 color patches. 6 of them are achromatic. The reflectance data of the target are freely available at BabelColor® (www.babelcolor.com). The data are provided in the wavelength region from 380 to 730 nm with 10 nm wavelength interval.

All calculations have been done with the software LabView® (National Instruments, Inc.). For calculating a single spectral reflectance value (denoted with *R*) of a certain patch of the color

Table 2
Wavelength parameters of the used 18 LEDs.

Type	Given peak WL [nm]	Peak WL [nm]	Center WL [nm]	Centroid WL [nm]	Domin. WL [nm]	FWHM [nm]	CIE *x*	CIE *y*
VL390-5-15	390	393.8	395.1	399.0	445.2	12	0.161	0.014
VL410-5-15	410	409.0	409.0	412.2	434.0	14	0.167	0.008
LED430-06	430	430.8	431.3	434.2	440.6	17	0.164	0.011
LED450-03	450	456.9	457.3	460.1	462.3	19	0.140	0.034
B5B-437-IX	468	472.8	473.5	476.1	476.4	29	0.105	0.098
LED490-03	490	496.1	496.8	500.0	498.1	24	0.014	0.491
B5-433-B505	505	502.7	504.6	509.2	507.2	28	0.008	0.698
B5-433-B525	525	526.3	527.7	530.7	533.4	35	0.181	0.789
LED545-01	545	540.6	542.3	545.7	548.8	32	0,293	0..700
LED565-33 U	565	566.3	566.4	574.4	571.3	27	0.453	0.546
B5-433-20	572	572.6	571.4	570.0	570.1	13	0.445	0.554
CY5111A-WY	590	593.0	592.2	591.0	589.9	13	0.575	0.425
LED610-03 V	610	614.4	613.2	611.8	608.2	14	0.660	0.340
B5-435-TL	628	635.8	634.2	632.6	623.7	17	0.699	0.301
ELD-650–523	650	645.2	643.5	641.5	632.1	13	0.711	0.289
ELD-670–524	670	666.6	667.3	666.4	646.8	23	0.724	0.276
LED690-03AU	690	680.0	680.1	678.6	654.1	24	0.728	0.272
LED710-01AU	710	712.3	712.1	711.1	638.7	24	0.718	0.282