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Further development of an LED-based radiation source for goniometric spectral radiance factor measurements

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Abstract

In previous work, the suitability of LEDs as a radiation source for the gonioreflectometer was investigated. An LED-Sphere Radiator (LED-SR) was constructed and its essential properties were described [1]. Based on these investigations, the further development of the LED-SR is presented here. Significant improvements such as a specially developed high-power LED board and active temperature control have been made. Due to the great influence of the reflecting insert on the radiation characteristics of the sphere, its optical and mechanical properties have also been optimized.

Investigations with respect to these modifications and their effects are explained. The achieved improvements and the performance of the LED-SR are evaluated in comparison to measurements with the typically used halogen sphere radiator (Halogen-SR). It can be shown that with the new radiator more accurate results can be obtained in the observed spectral range in a shorter measurement time.

Index Terms: High-power LEDs, gonioreflectometer, radiance factor, sphere radiation source, LED-Sphere Radiator (LED-SR)

1 Introduction

Reflection properties of materials are characteristic material-specific quantities and are important information for optical metrology, various research areas and for many applications, found e.g. in paper, textile and paint industries. Here, the spectral radiance factor $\beta(\lambda)$ for diffuse reflecting samples is of particular interest.

PTB's gonioreflectometer is used to determine the absolute spectral radiance factor $\beta(\lambda)$ for almost any irradiation and detection angle relative to the surface normal of the specimen [2]. The suitability of LEDs as a radiation source for the gonioreflectometer was previously investigated. For this purpose, a preliminary version of an LED-SR was constructed and its basic properties were described [1]. In further consecutive developement the features of the radiator were modified, leading to the current version. In the following different development details and the final performance of the LED-SR will be outlined.

2 Improvement of the LED-SR

The new model of the LED-SR (Figure 1) is based, like the former version, on the integrating sphere principle of the long-time existing Halogen-SR [3]. The shell of the integrating sphere is made of aluminium and includes an inner part with a diameter of 150 mm, made of sintered PTFE, which has a higher diffuse reflectivity in the short wavelength spectral range compared to the typically used barium sulfate coating.

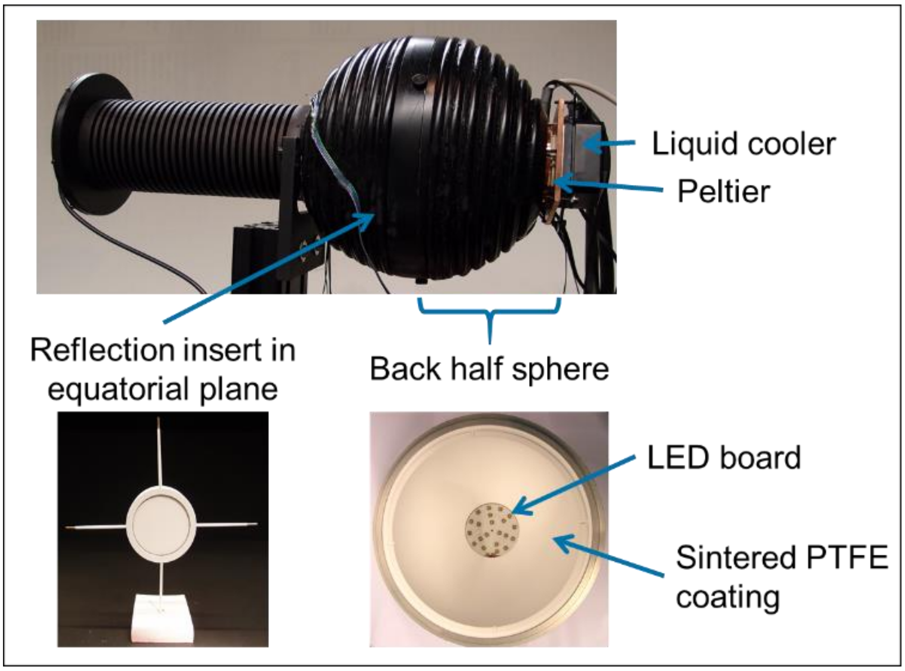


Figure 1: Structure of the improved LED-SR with sintered PTFE coating, a high-power LED board and its active temperature control system.

The individual LEDs used as primary source for the former LED-SR model were replaced by a specially designed high-power LED board consisting of 21 surface-mounted LEDs (SMD LEDs), covering a similar spectral range (peaks at 365 nm, 385 nm and 410 nm). This high-power LED board delivers a higher radiation power (section 3.1) and serves as a basis for a future modular system in which LED boards for different spectral ranges can be exchanged.

An active temperature control system was added to the LED-SR. This high-precision thermoelectric system controls the temperature of the emitter board from the backside. It significantly improves the temperature-dependent temporal stability of the LED-SR compared to the previous version (see section 3.1).

An internal reflector consisting of a barium sulfate coated aluminium plate is mounted in the center of the sphere. Barium sulfate was used here because it offers the possibility of in-house coating and thus ensures optimized surface quality of the reflector, as this is crucial for the measurement principle. The reflector serves as the emitting surface of the radiator and prevents direct emission by the sphere.

The specific position of the reflector inside the sphere has great influence on the emission characteristics [4] and thus on the accuracy of the measurement. To obtain a homogeneous beam profile the position can be adjusted in longitudinal direction. The optical and mechanical properties of the reflector were also improved in the new LED-SR model. Any remaining unevenness of the surface of the reflection insert seen in the previous model of LED-SR were eliminated and the mechanical centering in perpendicular direction was optimized, resulting in a higher homogeneity of the radiation field, which in turn improves the radiation distribution on the sample.

3 Results and Discussion

To study the contributions of the development steps of the LED-SR the essential properties such as the spectral range and coverage, the temporal stability, and the homogeneity of the radiation field on the sample surface were analyzed. Also, the influence of the mechanical centering of the reflective insert was investigated.

3.1 Characterization of the improved LED-SR

The spectral irradiance of the new LED-SR model in comparison to the previous model and the Halogen-SR is shown in Figure 2.

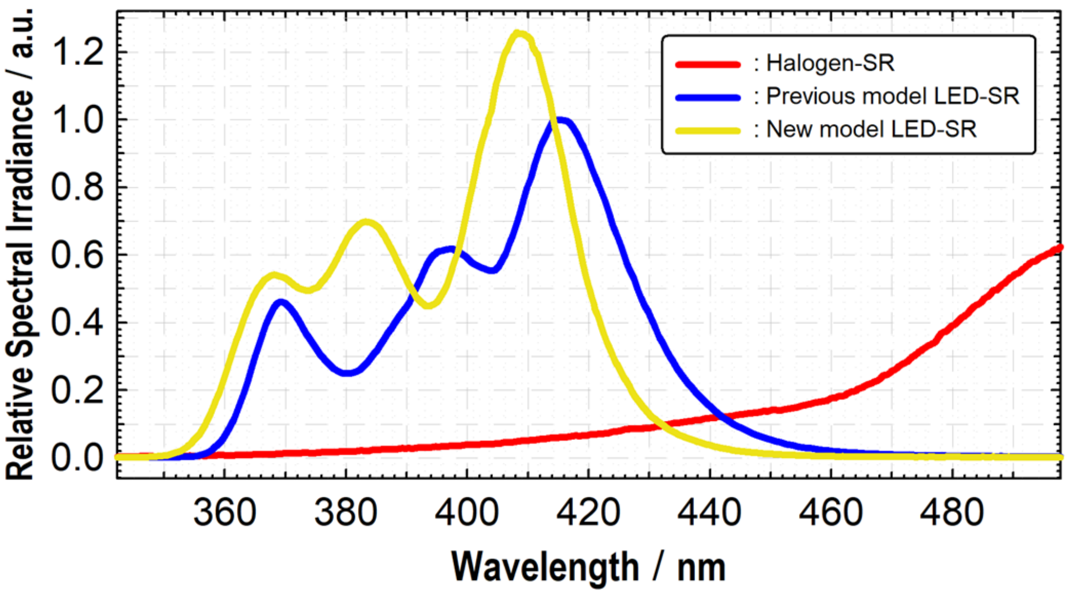


Figure 2: Relative Spectral irradiance of the Halogen-SR (red), the previous model of the LED-SR (blue) and the new LED-SR model (yellow).

The new LED-SR's spectrum is a superposition of the emission features of the three chosen SMD LED-types.

The output power break-even point for the new model shifts from 442 nm to 432 nm, but it delivers a higher radiation power below 390 nm. The individual LEDs of the previous LED-SR model required different power ratings and performance conditions such as heat generation or dissipation. The SMD LED types used for the new LED-SR model possess identical electrical and thermal requirements as well as a comparable aging behavior, thus offering better maintainability and long-term stability compared to the previous model.

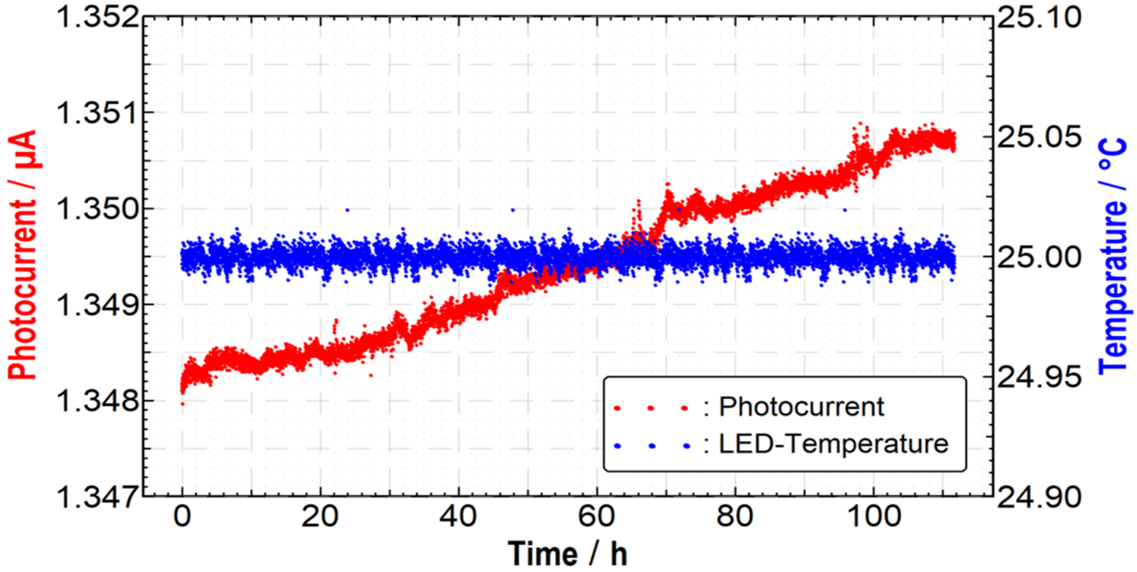


Figure 3: Emitted photocurrent (red) and temperature of the LED board (blue). The photocurrent was recorded with a Hamamatsu Si-Photodiode (S1337-1010BQ) and a Keysight digital multimeter (B2985A).

The long-term behavior of the broad-band emission of the LED-SR was measured for over 110 h by using a high precision silicon photodiode (Figure 3). The drift of the photocurrent of the previous version was about 0.25 % in 50 h and showed an oscillation of the photocurrent, which could mainly be attributed to the passive temperature control [1]. The added active temperature control now eliminates any temperature-dependent oscillation. With optimized temperature control settings, a final LED-board temperature stability of ± 0.02 °C was realized. The final achieved photocurrent drift is around 0.17 % in 100 h and meets the stability requirements of the target setup.

3.2 Reflection insert and homogeneity of the radiation field

The uniformity of the emission distribution of the integrating sphere can be optimized mainly by varying the longitudinal position of the internal reflector. A detailed overview of the measurement setup and the measurement procedure is given in [3].

The achieved homogeneity of the beam profile for the former model of the LED-SR was in the range of ± 0.5 %. This result was only slightly worse compared with homogeneity of the typically used Halogen-SR. It must be noted that the surface of the available reflection inserts used for that investigation had two areas with small unevenness causing this slight inhomogeneity.

For the improved LED-SR the reflection insert was newly primed and any remaining unevenness of the surface of the reflection insert was eliminated. Repeating the selection process [1][3] to find the optimum position of the reflection insert, for the new LED-SR a better homogeneity of ± 0.3 % was achieved. Thus, the homogeneity of the radiation field is comparable with that of the Halogen-SR (Figure 4).

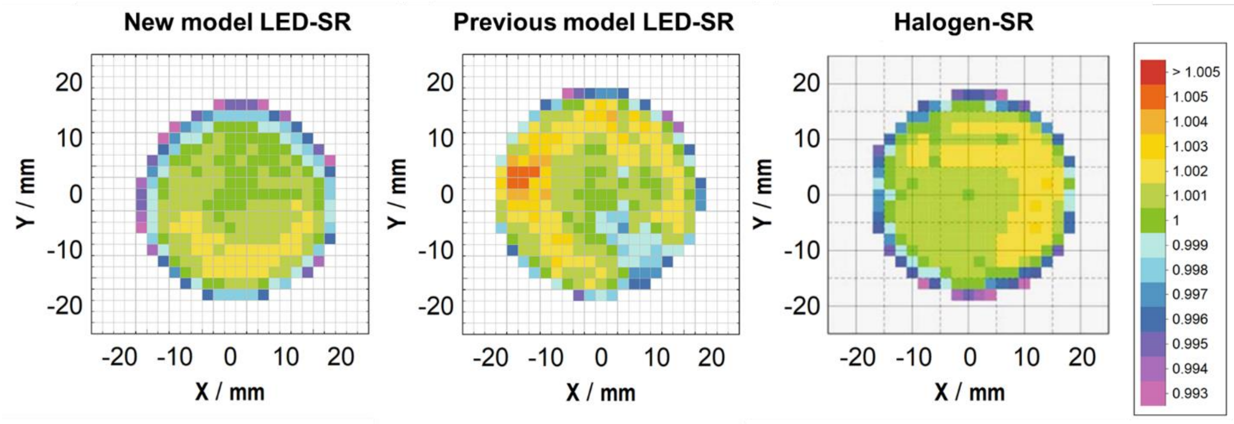


Figure 4: Two-dimensional homogeneity plot of the emitted radiance of the improved LED-SR (left side) compared with the previous model of the LED-SR (center) and the Halogen-SR using a 200 W quartz-tungsten halogen lamp (right side, picture taken from [3]). Distributions are normalized to the center value.

It has been shown that the equatorial and longitudinal position and also the mechanical centering of the reflector has big effects on the radiation characteristics of the sphere [4]. Therefore, not only the longitudinal position was optimized but also the quality of the transverse centering of the reflection insert was investigated.

For this purpose, a camera with a large high-resolution imaging CCD and a telephoto lens (f=80 mm) was placed at the sample position perpendicular to the radiation source. The camera was used to examine the radiation distribution at the sample position. Therefore, the camera was moved to the center, and the right and left edge of the measurement spot, referred to as positions 1, 2 and 3 in the following. A sketch of the measuring principle is shown in Figure 5.

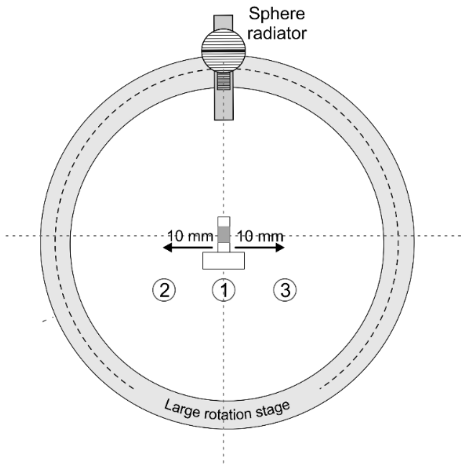
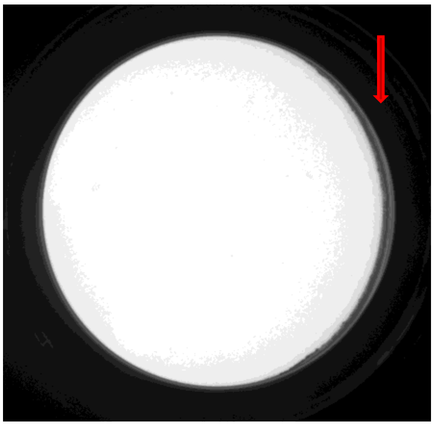
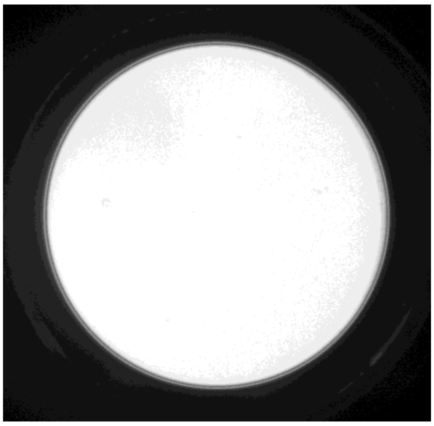


Figure 5: Sketch of the measurement procedure to determine the mechanical centering of the reflection insert. Position 1: camera centered in the sample plane. Positions 2/ 3: camera at the right/left edge of the measurement spot (Ø 20 mm)

The dark-frame-subtracted beam recordings depict a slight contribution of the rim of the holder for position 2, whereas for positions 1 and 3 the radiation field was homogeneously illuminated. A geometrical calculation showed that the insert had to be shifted by 1.8 mm. This mechanical displacement is caused by the transverse positioning of the reflective insert and is therefore not noticeable in position 1 and in the previous homogeneity beam distribution studies, where the equatorial and longitudinal positions were optimized. However, it does influence the sample illumination and thus the measured reflection properties. Therefore, the mechanical centering was improved, resulting in a homogeneous beam distribution falling on the sample in all three positions (Figure 6).



Before mechanical centering



After mechanical centering

Figure 6: LED-SR beam recording for position 2 before (left) and after (right) correction of the mechanical centering. The observed rim of the holder is marked by a red arrow.

3.3 Performance of the LED-SR in the final measuring setup

The LED-SR was implemented in the gonioreflectometer setup to perform comparative measurements with the currently used Halogen-SR. For this purpose, the absolute spectral radiance factor $\beta(\lambda)$ of a white ceramic was measured with both sources, each with seven repetitions with an angle of incidence $\theta_i = 45°$, angle of detection $\theta_r = 0°$. The resulting mean absolute spectral radiance factor $\beta(\lambda)$ with a coverage factor of $k = 1$ is shown in Figure 7. The determined values with both radiation sources agree with each other within their uncertainty margin. Nevertheless, a rising divergence of the curves below 385 nm can be observed. This may be due to the decreasing signal of the Halogen-SR and the declining sensitivity of the used silicon photodiode. To compensate for this, a more sensitive detector type can be applied.

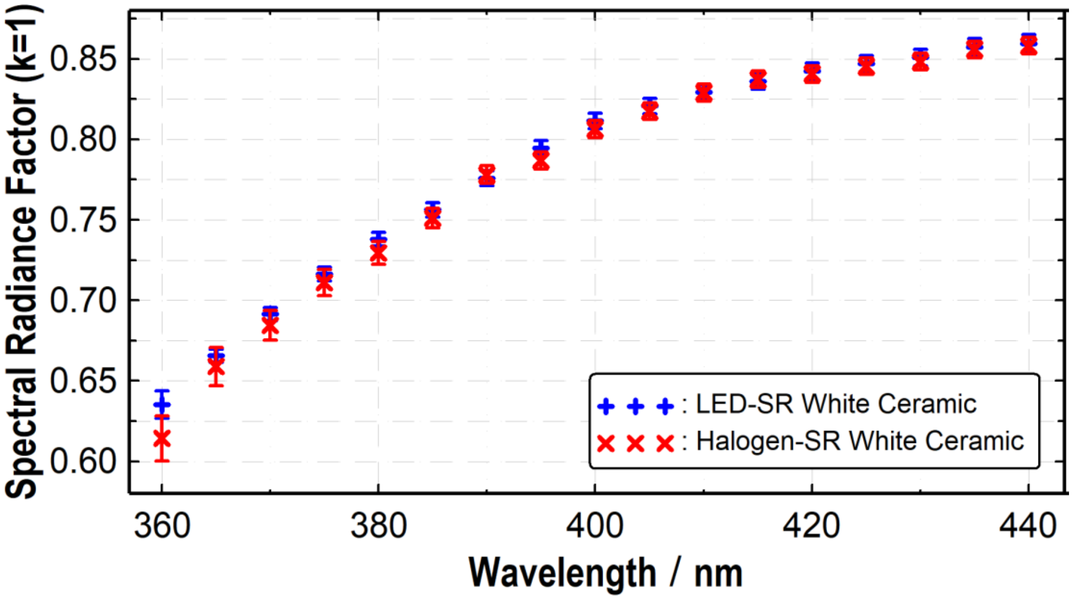


Figure 7: Absolute spectral radiance factor β(λ) (k = 1) for a white matte ceramic sample measured with the LED-SR and Halogen-SR in 45°:0° geometry. A silicon diode (Hamamatsu S1337-66 BR) was used for detection in the entire spectral range.

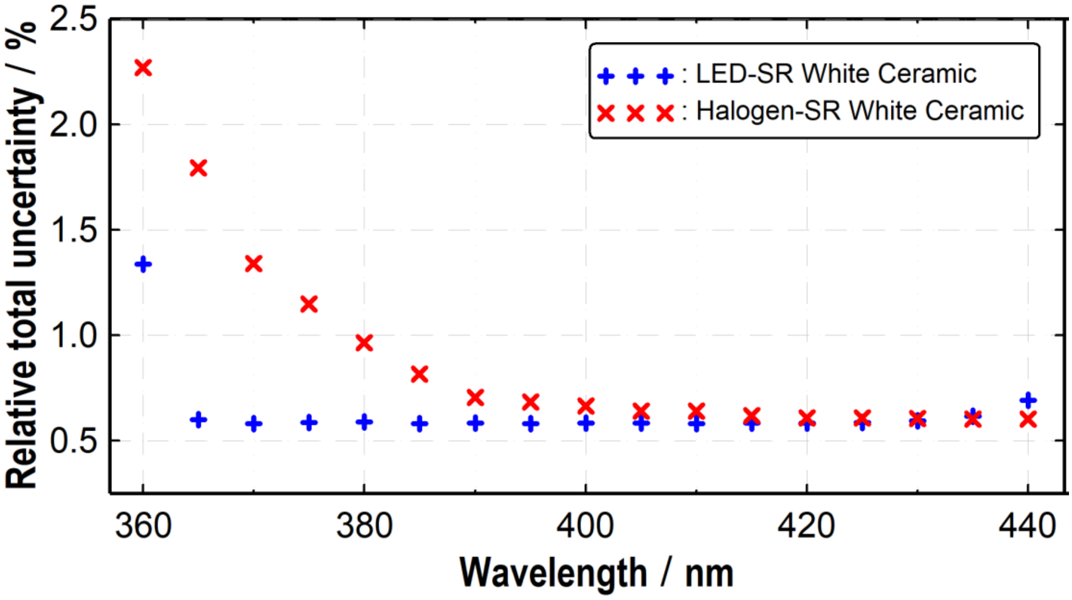


Figure 8: Relative total measurement uncertainty (k = 1) of the absolute spectral radiance factor for a white matte ceramic sample measured with the LED-SR and Halogen-SR in 45°:0° geometry.

The total measurement uncertainty of the spectral radiance factor, which is composed of statistical and systematic uncertainty contributions, is smaller for the LED-SR in its designed spectral range (Figure 8). This is mainly due to smaller standard deviations resulting from the high radiant power and stability of the LED-SR, which are the strongest influence on the statistical uncertainty contributions. Due to its decreasing output power in this spectral range the Halogen-SR shows increasing signal instability, associated with a correspondingly increasing standard deviation and thus statistical uncertainty contribution. Most of the systematical uncertainty contributions are equal for both sources. Compared to the Halogen-SR, the spectrum of the LED-SR is more structured due to the spectral emission characteristics of the LEDs. This leads to a relatively large spectral bandwidth-related uncertainty. This uncertainty contribution is larger for the LED-SR than for the Halogen-SR. However, also considering this contribution, the LED-SR still shows a smaller total uncertainty in its design wavelength range of 360 nm to 430 nm. A paper which presents the entire measurement uncertainty consideration in detail is in preparation.

4 Conclusion and outlook

Further developments were made on a preliminary LED-SR model. The previously used single LEDs were replaced by an especially developed high-power LED board and a highly precise active temperature control was added. The optical and mechanical properties of the reflecting insert of the new LED-SR model was modified and improved, leading to better radiation characteristics. The achieved improvements were characterized based on key properties such as spectral coverage, temporal stability and homogeneity of the radiation field. They all meet the necessary requirements for the implementation of the new LED-SR in the gonioreflectometer-setup to determine the spectral radiance factor. The performance of the LED-SR was evaluated in comparison to measurements with the Halogen-SR. The validation measurements show that even with just a few measurements cycles the application of the new LED-SR model leads to a significant improvement with respect to the achievable measurement uncertainty in the spectral range between 360 nm and 430 nm. Thus, the LED-SR can be considered as a robust and suitable radiation source for measurements at the border between visible and UVA wavelengths for the gonioreflectometer. The applied principle can be extended to other wavelength ranges, especially to UVB, where modern radiation sources with appropriate power are already available.

5 Acknowledgement

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6 References

[1] I. Santourian, S. Teichert, K.-O. Hauer, A. Schirmacher, Investigation of the suitability of high-power LEDs for the use as radiation source for PTB’s gonioreflectometer, TU Ilmenau, Lux junior 2019, pp. 43-50, 2019

[2] D. Hünerhoff, U. Grusemann, and A. Höpe, “New robot-based gonioreflectometer for measuring spectral diffuse reflection”, Metrologia, BIPM and IOP Publishing Ltd, Vol. 43, No. 2, pp. 1-10, 2006

[3] K. Hauer and A. Höpe, “High-grade uniform light source for radiometric and photometric applications”, MAPAN, Springer Science+Business Media S.A., Vol. 24, No.3, pp. 175-182, September 2009

[4] W. Erb and L. Mücke, Untersuchungen der Abhängigkeit des Strahldichtefaktors diffus angestrahlter Reflexionsnormale vom Abstrahlungswinkel, Lichttechnik 4, 210,1972