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White light quality of phosphor converted light-emitting diodes: A phosphor materials perspective of view

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ABSTRACT

For a systematic approach to improve the white light quality of phosphor converted LEDs and to fulfil the demands for colour temperature reproducibility and constancy, it is imperative to understand how variations of the extinction coefficient and the quantum efficiency of the phosphor particles as well as variations of the excitation wavelength of the blue LED die affect the correlated colour temperature of the white LED source. Based on optical ray tracing of a phosphor converted white LED package we deduce permissible values for the variation of a given extinction coefficient and a given quantum efficiency of a phosphor material in order to maintain acceptable colour variations. These quantitative valuations of the required constancy of the optical properties of the phosphors will in particular provide some benchmarks for the synthesis of improved phosphor materials aiming at solid state lighting applications.

1. Introduction

There is no doubt that a replacement of the conventional lighting sources by light-emitting diodes (LEDs) will reduce energy consumption, save resources due to their long life-time and will also have a beneficial climate impact [1]. Today's most common approach for white light-emitting diodes relies on a combination of blue LED light and excited emission from a phosphor material [1–4]. Latter is part of the colour conversion element (CCE), which typically consists of phosphor particles embedded in a transparent silicone matrix. Although this concept seems to be rather trivial, recent studies have highlighted that the performance of solid state lighting sources in terms of light output and quality of the white light critically depends on the appropriate shape, composition and arrangement of such CCEs within the LED package [5–19].

One important aspect in the context of white light quality is the highly accurate reproducibility of the desired correlated colour temperature (CCT) among individual LEDs, which for general lighting purposes should be within a 2-step MacAdam ellipse [20]. This is a challenging demand since imprecisions of the manufacturing and fabrication processes of the LED packages and its components involve a lot of potential failure sources for colour deviation. In addition, for most of the phosphors the excitation spectrum shows strong wavelength dependence in the blue range of the visible spectrum. This means that the magnitude of phosphor excitation is strongly affected by wavelength variations of the blue LED dice.

In recent publications we have highlighted that also the phosphor particle sizes and the CCE composition have to be precisely controlled in order to guarantee colour constancy among individual LED packages. For example, even though the overall phosphor concentration within a CCE is kept constant, a variation of the phosphor particle diameter may cause changes of the respective colour temperatures because of varying single particle scattering functions for different phosphor particle sizes [21]. In addition, the respective single particle scattering function for a given phosphor particle diameter is also affected by the refractive index of the surrounding silicone matrix material. A variation of the refractive index of the silicone therefore also modifies the resulting colour temperature [15]. Moreover, for each phosphor particle size the light extraction efficiency from the LED package can be optimized by choosing an appropriate refractive index of the matrix material [15]. Also the constancy of the phosphor distribution within the matrix is of high relevance for colour temperature reproducibility. Deviations from a given phosphor distribution, for example as a result of phosphor settlement upon curing of the silicone matrix, again result in variations of the respective chromaticity coordinates [22] of the white LED source. However, while in these previous studies the impact of variations of the phosphor particle sizes and phosphor particle distributions as well as the refractive indices of the matrix material were investigated, the optical properties of the phosphor particles themselves were considered to be constant. In order to gain a better understanding on the individual phosphor material related sources

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for colour deviation and their respective magnitudes, in the following we extend our previous investigations and discuss the impact of variations of the optical properties of a phosphor on colour temperature reproducibility and constancy of phosphor converted LEDs.

Nowadays, a large number of new phosphor materials for solid state lighting applications are synthesized by materials scientists in order to cover the whole palette of colours and to enhance and to optimize the extinction coefficient and the quantum efficiency of the phosphors [23–37]. In a recent publication Smet et al. [24] summarized some of the requirements phosphors have to fulfil in order to be acceptable as colour conversion materials in high power LEDs. Despite demands like a broad band emission to guarantee a high colour rendering index and the absence of emission saturation at high fluxes, important characteristics for applicable phosphors as reported by the authors are an excitation spectrum showing good overlap with the pumping LED, a relatively flat excitation spectrum near the peak emission of the LED, an emission spectrum, excitation spectrum and a quantum efficiency that remain unchanged at elevated temperatures and excellent chemical and temperature stability [24].

However, usually only quantitative values as measured for the phosphor materials themselves with respect to these characteristics are reported in the literature. We therefore aim to discuss the requirements on the reproducibility as well as the temperature and long-term stability of the excitation and emission properties of a phosphor material from the lighting perspective of view. Based on optical ray tracing of a phosphor converted white LED package we deduce permissible values for the variation of a given extinction coefficient and a given quantum efficiency of a phosphor material in order to maintain acceptable colour variations upon solid state lighting applications. Besides some useful input for the development and synthesis of new phosphor materials as well as a quantification of the requirements for chemical and temperature stability upon device operation, such a valuation will be also helpful for a specification of the requirements for batch to batch reproducibility of the optical properties of a phosphor material selected for high-mass fabrication.

As one example for an optimized CCE geometry with respect to a reduced angular variation of the respective CIE x chromaticity coordinate, a width of $b = 1040\ \mu\text{m}$, a height of $h = 400\ \mu\text{m}$ and a phosphor concentration c of 10 vol.% has been identified in our previous studies [14], considering phosphor particles with a mean diameter of 7.8 μm and a standard deviation of 4.2 μm as well as an extinction coefficient of the yellow phosphor particles that is set to zero for $\lambda = 565$ nm and 1×10^{-3} for $\lambda = 460$ nm. In addition, for these studies the assumption was made that every absorbed blue photon is converted into a yellow photon, which means that the quantum efficiency of the yellow phosphor particles is 100%.

In the following we will use this CCE composition and materials parameters as well as the corresponding CIE chromaticity coordinates upon excitation with a blue LED die as a reference system and will derive some limits of permissible variations of the optical properties of the phosphor material, in particular of the extinction coefficient and the quantum efficiency, in order to maintain acceptable colour deviations upon device operation.

2. Experimental

The details of the simulation procedure can be found in our previous publication [14]. Generally, the simulation procedure, that was carried out with the commercial software package ASAP™, relies on the set-up of an appropriate simulation model for a blue emitting LED die and the implementation of a square-shaped CCE with a flat surface on the top of the die (see Fig. 1 for a sketch of the simulation model).

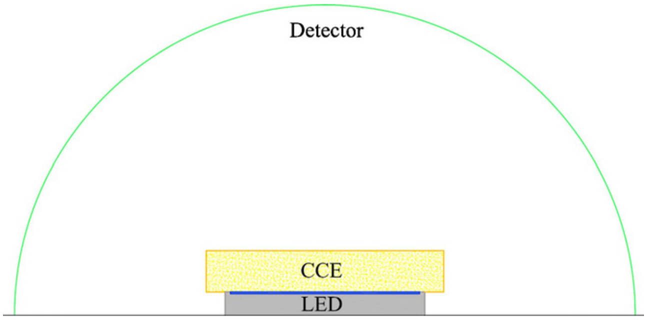

Fig. 1. The simulation model consists of a blue emitting LED die with a square-shaped CCE placed on top of it and a hemispherical detector with a radius of 4 cm. The hemispherical detector is divided into 101 pixels along the two perpendicular main axes. The blue emitting LED die consists of an emitting area with dimensions of 940 μm × 940 μm and gold pads for wire bonding in two neighbouring corners, which are placed on top of a silicon substrate. The silicon substrate has dimensions of 990 μm × 990 μm and a height of 100 μm. The CCE has a width of 1040 μm and a height of 400 μm. The concentration of the phosphor particles in the silicone matrix is 10 vol.%.

Two wavelengths are considered in the simulations: one representing the blue LED light (460 nm, CIE chromaticity coordinates CIE $(x,y) = 0.143, 0.029$, CIE1931) and the other one the converted yellow light (565 nm, CIE $(x,y) = 0.408, 0.589$, CIE1931). When mixing those wavelengths, the CIE chromaticity coordinates are in any case located on a straight line between 460 and 565 nm in the corresponding CIE 1931 colour space and are therefore linearly interdependent, which means that even a single chromaticity coordinate – for example CIE x – is sufficient for defining the result. For the particular two wavelengths of 460 and 565 nm, the colour space distance of the combined spectrum from the Planckian curve is stronger for the CIE y than for the CIE x coordinate, especially for lower colour temperatures. In practise, a small amount of another phosphor material with a more reddish emission spectrum can be added to the CCE, which moves the CIE y coordinate closer to the Planckian curve and simultaneously improves the colour rendering index. However, since the main focus of this study is to evaluate the impact of variations of the extinction coefficient and the quantum efficiency of the phosphor material on the variations of the respective CIE chromaticity coordinates, this fact is of minor importance, in particular for nearby areas within the CIE chart.

It is assumed that only the blue LED light is absorbed by the yellow phosphor particles, therefore the extinction coefficient of the yellow phosphor particles is set to zero for 565 nm and to 1×10^{-3} for $\lambda = 460$ nm. Both the blue LED light and the yellow converted light are scattered throughout the CCE. The simulation of this scattering process is based on the scattering model of Mie and considers the particle size distribution of the phosphor, and the optical properties of both the matrix material and the phosphor. In the present study, both the extinction coefficient and the quantum efficiency of the phosphor material are varied, while the refractive indexes of the silicone and the phosphor are kept constant at 1.4 and 1.63 for both wavelengths. Similarly, the mean diameter of the phosphor particles is kept constant at 7.8 μm with a standard deviation of 4.2 μm.

In a final step of the simulations, the light distribution is inspected by a "detector element" of favoured shape, which gives the light distribution at an area of interest in the far field of the LED package. In the following the detector element is assumed to have a hemispherical shape with a radius of 4 cm and is divided into 101 × 101 pixels (in direction of the x and y principle axes). The detector is centrically placed above the LED package, see Fig. 1. In the present study, the overall CIE x and CIE y values were calculated from the ratio of the respective fluxes of the blue and the converted yellow light as determined by the detector element.

3. Results and discussion

Figs. 2 and 3 show the impact of variations of the extinction coefficient and the quantum efficiency of the phosphor particles on the overall CIE x chromaticity coordinate of the reference system.

In case of Fig. 2, the value of the extinction coefficient of the phosphor particles for the blue light is varied from that of the reference system, 1×10^{-3}, to values in between 1×10^{-2} and 1×10^{-4}, while the quantum efficiency remains constant at 100%. Contrarily, in Fig. 3 the quantum efficiency of the yellow phosphor particles is varied in addition in steps of 10% in between 100% and 50%. A quantum efficiency of e.g., 50% means, that for each absorbed blue photon, 0.5 photons of converted yellow light are emitted.

From both figures it becomes evident, that a variation of these parameters has a significant bearing on the overall CIE x chromaticity coordinate. These variations are mostly pronounced for CIE x values of about 0.33, since for these CIE x values both the blue

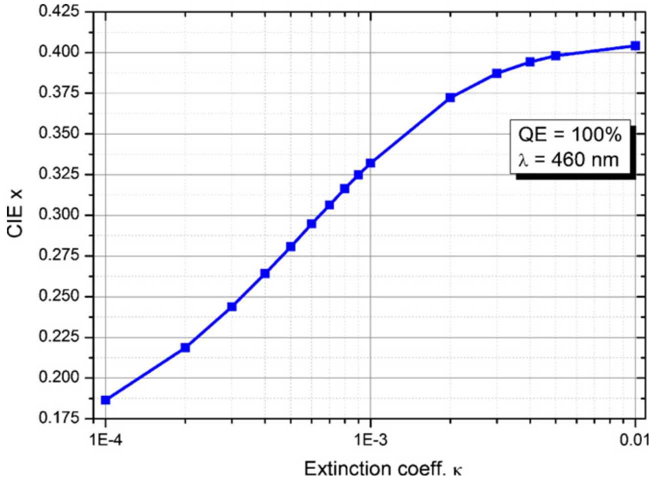

Fig. 2. Dependency of the CIE *x* chromaticity coordinate on the extinction coefficient of the phosphor particles. The extinction coefficient is varied in between 1×10^{-2} and 1×10^{-4} while the quantum efficiency remains constant at 100%.

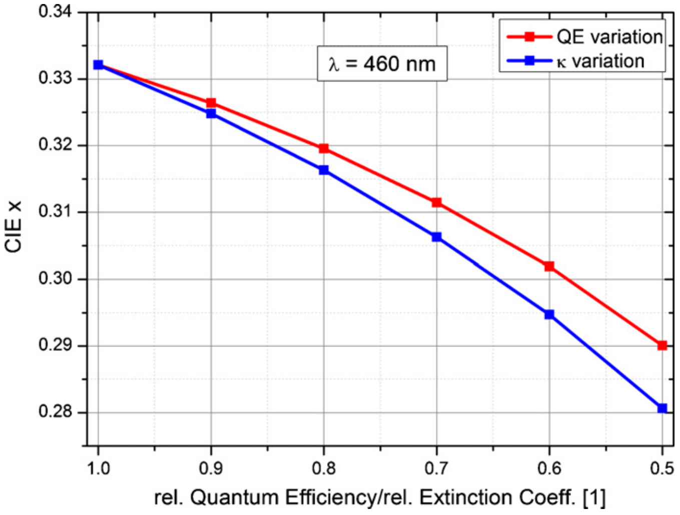

Fig. 4. Dependency of the CIE *x* chromaticity coordinate on the quantum efficiency and the extinction coefficient. Both the quantum efficiency and the extinction coefficient of the reference system are varied in steps of 10%.

light and the yellow light notably contribute to the overall emission spectrum.

Fig. 4 compares the variation of the CIE *x* chromaticity coordinate with respect to alterations of the quantum efficiency and the extinction coefficient of the phosphor material a little bit more in detail. Starting from the respective values for the extinction coefficient and the quantum efficiency of the reference system, 1×10^{-3} and 100%, both the extinction coefficient and the quantum efficiency were reduced in steps of 10%. As evident from Fig. 4, in comparison with the quantum efficiency, the reduction of the extinction coefficient causes a little bit stronger variation of the CIE *x* coordinate to the bluish. This means, that the variation of the extinction coefficient has a little bit higher impact on the variation of the CIE *x* chromaticity coordinate than the quantum efficiency has. This effect can be attributed to the different ratios of the blue and the yellow fluxes obtained for the different values of the optical properties of the phosphor material. Starting with a ratio of 0.33 for the blue and yellow fluxes of the reference system, for an extinction coefficient of 1×10^{-3} and a quantum efficiency of 50% this ratio increases to 0.66 and to 0.76 for an extinction coefficient of 5×10^{-4} and a quantum efficiency of 100%.

In order to quantify the magnitude of these variations and their relevance for colour deviation in solid state lighting sources more in detail, Fig. 5 depicts the CIE *x* and CIE *y* values of the reference system, 0.3321 and 0.4276 together with the corresponding MacAdam ellipse of step 4 (red line) and step 5 (black dashed line). MacAdam ellipses of step 4 and step 5 are chosen in this figure, since these are typical values present day's solid state lighting sources are specified for.

As evident from this image, a reduction of the quantum efficiency of the phosphor from 100% to 90% causes a deviation from the initial CIE chromaticity coordinates, which is clearly located inside a MacAdam ellipse of step 4, while a reduction of the quantum efficiency of the phosphor to 80% causes a chromaticity coordinate variation which by far is located outside a MacAdam ellipse of step five.

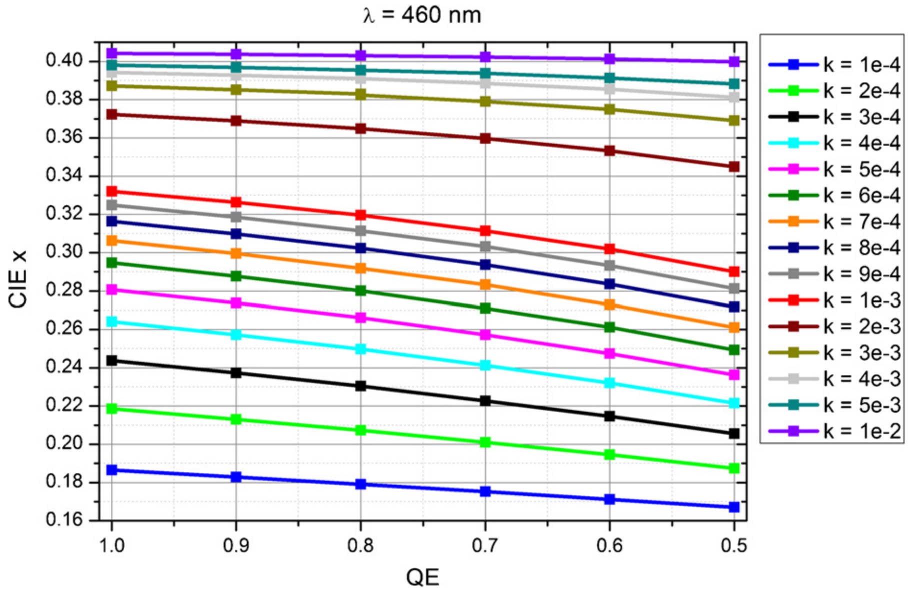

Fig. 3. Dependency of the CIE *x* chromaticity coordinate on the quantum efficiency of the phosphor particles. The quantum efficiency is varied in between 100% and 50% in steps of 10% for extinction coefficients in between 1×10^{-2} and 1×10^{-4}.

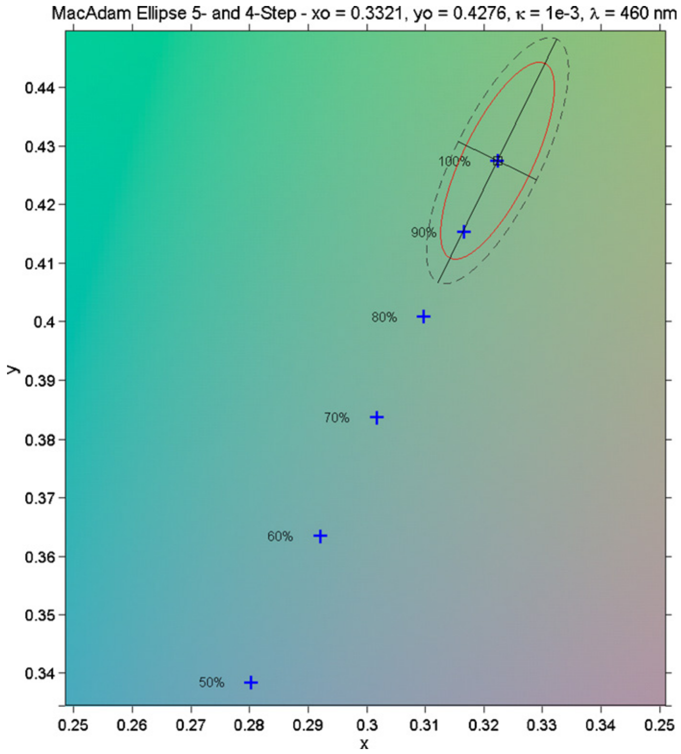

Fig. 5. Dependency of the CIE *x*,*y* chromaticity coordinates on the quantum efficiency of the phosphor particles. The quantum efficiencies of the phosphor are varied in between 100% and 50%. The red line corresponds with a MacAdam ellipse of step 4, the dashed black line with a MacAdam ellipse of step 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

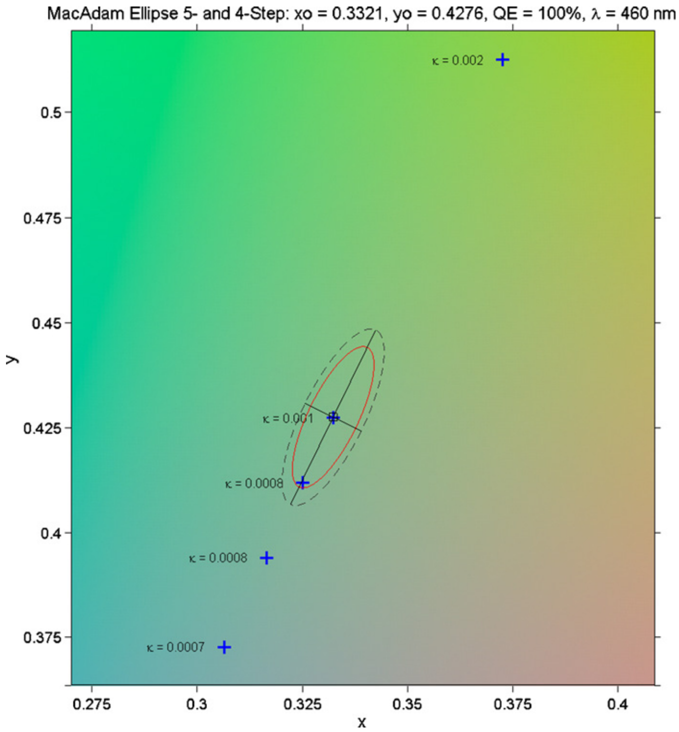

Fig. 6. Dependency of the CIE *x*,*y* chromaticity coordinates on the extinction coefficient of the phosphor particles for extinction coefficients in between 2×10^{-3} and 7×10^{-4}. The red line corresponds with a MacAdam ellipse of step 4, the dashed black line with a MacAdam ellipse of step 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

From Fig. 6, a similar impact also becomes evident for potential variations of the extinction coefficient of the phosphor particles. As shown in Fig. 6, a reduction of the extinction coefficient by 10% results in a colour deviation which, in comparison with the CIE chromaticity coordinates of the reference system, is just inside the range of a MacAdam ellipse of step 4.

Taking into consideration, that, as previously stated [20], for white LEDs to be accepted broadly for general lighting applications, the colour variations among individual LEDs should become of the order of a 2-step MacAdam ellipse, the tremendous role of variations of the extinction coefficient and the quantum efficiency of the phosphor particles on the reproducibility of a desired colour temperature becomes apparent.

In addition, in reality one has to consider combinations of a lot of different failure sources which will sum up to a final colour deviation. For example, also the emission wavelength of the blue LED die may vary from one die to the other. Even if it were possible to deposit exactly the same amount of phosphor particles of identical optical properties on top of the individual LED dice, differences of the final colour temperatures are unavoidably caused by wavelength variations among these LED dice. In order to compare the effect of wavelength variations of the exciting wavelength with that of the optical properties of the phosphor, Fig. 7 considers also the effect of wavelength variations of the blue LED dice on the magnitude of CIE chromaticity coordinate variation with respect to MacAdam ellipses of step size 4 and 5 as well as a MacAdam ellipse of step size 2, which is the ultimate goal for colour constancy of solid state lighting sources. As evident from this image, variations of the exciting wavelength from 460 nm to 455 nm and to 465 nm cause colour deviations which are still clearly within a MacAdam ellipse of step 4. The above mentioned alterations of the optical properties of the phosphor material either to an extinction coefficient of 9×10^{-4} or to a quantum efficiency of 90% result in colour deviations which are comparably more pronounced than colour deviations due to these variations of the excitation wavelength. Combinations of these variations of the exciting wavelength and the optical parameters may in best-case counteract the individual magnitudes of chromaticity coordinate shift (e.g., an excitation wavelength of 465 nm and a quantum efficiency of 90%), however they may also amplify colour deviation, e.g., an excitation wavelength of 455 nm and a quantum efficiency of 90%.

Being aware of the problems caused by wavelength variations of the exciting blue wavelength on the reproducibility of a desired colour temperature, most of the white LED manufacturers take care to use very small wavelength bins of blue LED dice, which are in the order of 1–2 nm. However, as it becomes evident from these studies, at least a similar attention and accurateness should be also focused on the constancy of the optical properties of the phosphor materials. Compared with variations of the excitation wavelength of even 5 nm, the present study highlights that even small variations of the extinction coefficient and the quantum efficiency of the phosphor material cause variations of the CIE chromaticity coordinates which are of the same range or even larger. From a materials point of view, a reduction of the quantum efficiency of the phosphor by about 6% would result in a colour deviation matching the outer limits of a MacAdam ellipse of step 2, similarly for a reduction of the extinction coefficient to 0.95×10^{-3}. However, for both of these estimations all the other parameter were considered to maintain their optimal values, while in reality variations of each of these parameters will sum up to the final variation of the CIE chromaticity coordinates.

Therefore, it is evident, that similar strong criteria as in case of wavelength binning of the LED dice should be also considered for the optical properties of the phosphor materials. In addition one has also to consider that the reference system discussed in this study refers to a CIE *x* value in the range of 0.33. However, for higher

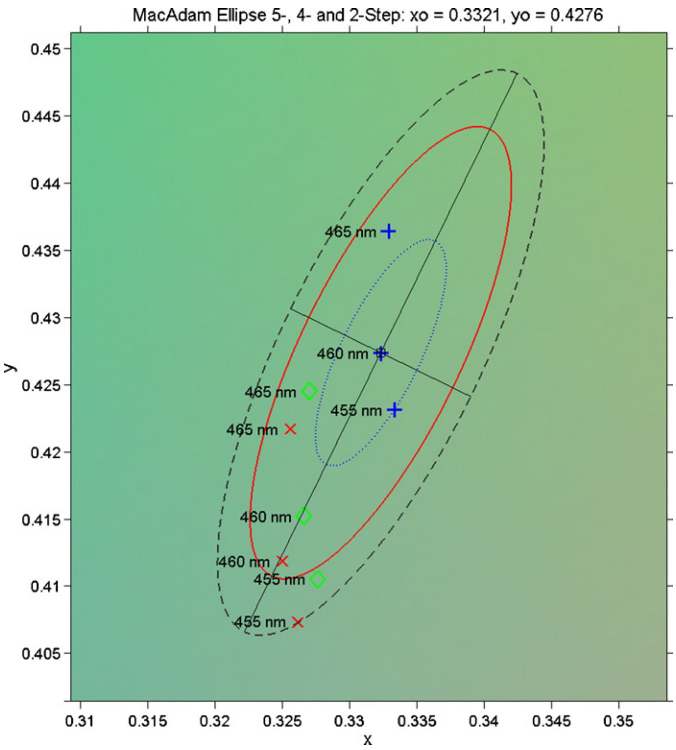

Fig. 7. Dependency of the CIE *x*,*y* chromaticity coordinates on the excitation wavelength of the blue LED die for excitation wavelengths ranging from 455 nm to 465 nm, extinction coefficients of 1×10^{-3} and 9×10^{-4}, as well as quantum efficiencies of 100% and 90% (+: $\kappa = 1 \times 10^{-3}$, QE = 100%, ×: $\kappa = 9 \times 10^{-4}$, QE = 100%, ◊: $\kappa = 1 \times 10^{-3}$, QE = 90%). The red line corresponds with a MacAdam ellipse of step 4, the dashed black line with a MacAdam ellipse of step 5. The blue dotted line represents a MacAdam ellipse of step size 2, which is the ultimate goal for colour constancy of solid state lighting sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

colour temperatures, as in case of LEDs with a more bluish white light emission, the dimensions of the respective MacAdam ellipses become even smaller. This means that for the fabrication of LEDs with higher colour temperatures the optical properties of the phosphor material have to be maintained even more accurately in order to match MacAdam ellipses of the same step values.

Considering the goal of a MacAdam ellipse of step 2 for all colour temperatures and taking all the different potential sources for colour deviation into consideration, which all can be limited but not fully eliminated, it becomes evident that the contributions of variations of the quantum efficiency as well as the extinction coefficient of the phosphor material should be limited to values in the range of about 1%, if procurable even lower.

Mass-fabrication of a phosphor selected for device fabrication should therefore focus on absolute batch to batch reproducibility with variations of the optical properties that do not exceed the 1% range. Considering all the different processing parameters, like the reaction atmosphere and temperature and the activator concentration [38,39], which all affect the properties of the final phosphor, a strict control of the processing conditions is absolutely necessary. Since also the respective single particle scattering functions of the phosphor particles show a strong dependence on the phosphor particle size, an exact control of the phosphor particle size is in addition of high relevance, regarding also the fact that the quantum efficiency of the phosphor particles itself may also vary with the phosphor particle size.

Despite reproducibility among individual batches of a phosphor material upon mass-fabrication, one has also to consider that the optical properties, in particular the extinction coefficient and the quantum efficiencies of most of the phosphor materials show a strong dependency on the temperature. From a phosphor materials perspective of view, the extinction spectrum should be flat around the peak wavelength of the exciting blue LED die [24] in order to assure an almost constant extinction coefficient upon small variations of this peak wavelength. Latter aspect is of particular importance, since the position of the peak wavelength of the blue LED die is also known to shift with temperature. For instance, as reported for high power blue LEDs, this wavelength shift might be as large as 6 nm for an increase of the junction temperature in between 25 °C and 150 °C [40]. Considering the results of Fig. 7, such large shifts may consume most of the tolerance range of MacAdam ellipses of small step sizes, leaving almost no additional tolerance ranges for variations of the optical properties of the phosphor materials with temperature.

Indeed, as recently reported by Bachmann et al. [41], the intrinsic quenching temperature of the Ce luminescence in YAG as measured for very small doping concentrations is in the range of 700 K, which would be far above even of the operational temperature of solid state lighting sources. However, temperature dependent measurements of the phosphors still showed a strong decrease of the integrated emission intensity for temperatures even far below 700 K [41]. This was attributed to a temperature dependent decrease of the absorption strength of the 460 nm absorption band, giving reason for a lower light output even if the quantum efficiency remains constant. Assuming that the lower integrated emission intensity is directly related to a lower absorption strength, a rough estimation of the results reported by Bachmann yields a temperature window of about 40 K for a reduction of the extinction coefficient of about 5%. Latter reduction might be just tolerable for colour variations of the reference system which are within a MacAdam ellipse of step two, assuming that this would be the only source for colour deviation. However, since e.g., the shape of the emission spectrum of the phosphor or the excitation wavelength of the blue LED die are also known to be prone to shift with temperature, it becomes evident that the tolerable range of temperature variation will be much smaller. Contrarily, for higher Ce concentrations, luminescence quenching due to thermally activated concentration quenching becomes the dominant loss mechanism for the integrated emission intensity, even at lower temperatures [41]. This means that in this case also a reduction of the quantum efficiency contributes to the lower integrated emission intensity observed.

Nonetheless, this example highlights that, as concluded also by Smet et al. [24], for a classification of the applicability of a phosphor for solid state lighting applications all the optical parameters have to be considered in a comprehensive way. Considering only one of these parameters might be an essential but a not sufficient criterion for the choice of an appropriate phosphor material. Even if the quantum efficiency of the phosphor remains constant within a large temperature range, a strong colour deviation of the solid state lighting source may occur in case that the constancy of the extinction coefficient within the same temperature range is not guaranteed.

Albeit for high power LED luminaries a specific colour temperature can be specified for a specific temperature of operation, the combination of all the potential sources of failure (deviations from the specified temperature of operation, corresponding shift of the peak wavelength of the blue LED die, . . .) again restricts permissible variations of the optical properties of the phosphor materials within the temperature range of operation to values in the range of 1% in order to guarantee MacAdam ellipses of small step sizes.

However, even if a desired colour temperature can be favourably adjusted for a specific operating temperature, an important aspect will be also the chemical stability of the phosphor material upon long time device operation. Considering again the other potential sources of failure that might contribute to long-term colour variation, like modifications of the optical properties of the matrix material [42], one can envisage that also for long-term colour stability variations of the optical properties of the phosphor material due to materials decomposition and degradation [43,44] should be limited to values in the range of 1%. Considering an expected lifetime of 25,000–50,000 h for solid state lighting sources, such a small tolerance range for materials degradation in order to guarantee long term colour deviations which do not exceed a MacAdam ellipse of step 2 will be one of the most challenging issues for phosphor material optimization.

4. Conclusions

Colour deviations in phosphor converted white LEDs are affected by a lot of parameters, ranging from imprecisions in repeated deposition of exactly the same amount of phosphor to wavelength variations of the blue LED dice. However, as shown in this study, colour deviation is also very sensitive with respect to variations of the optical properties of the phosphor materials. Small variations of either the extinction coefficient or the quantum efficiency of the phosphor particles similarly result in tremendous variations of the CIE chromaticity coordinates. For manufacturing purposes, it is therefore an essential issue to guarantee largely consistent optical properties of the phosphor particles with respect to batch-to-batch reproducibility as well as temperature and long-term chemical stability. In particular, as shown in this study, the deviations of the optical properties should be not larger than about 1% in order to guarantee colour deviations which do not exceed MacAdam ellipses of step 2. Latter value is seen as an ultimate goal for colour constancy of solid state lighting sources.

These quantitative valuations of the required constancy of the optical properties of the phosphors will in particular provide some benchmarks for the synthesis of new phosphor materials aiming at solid state lighting applications. In addition, since the integrated intensity of the phosphor emission depends on a complicated interplay of both the extinction coefficient and the quantum efficiency, one has to guarantee that these criteria for constancy are simultaneously fulfilled for all the optical properties. The constancy of e.g., the quantum efficiency within a large range of temperatures is a prerequisite for the choice of a phosphor material, but might be a not sufficient criterion if the extinction coefficient shows a larger variation within the same temperature range. Characterization and evaluation of a phosphor material should therefore comprise quantifications of all these parameters in order to allow for an estimation of its applicability as a conversion material in solid state lighting sources.

A further challenging issue for the development of new phosphors will be their chemical and physical stability, in particular the maintenance of these optical properties during the expected lifetimes of solid state lighting sources, which again should not deviate from the initial values by more than about 1%.

While in particular CCEs composed of phosphor particles embedded in a silicone matrix, which is at present day the most common CCE technology, are prone to be affected by a strong temperature loading [45] upon device operation, recent progress in colour conversion technology may diminish this problem to some extend. For example, in comparison with CCEs composed of phosphor particles embedded in a silicone matrix, glass–ceramic [46] and ceramic [47–49] phosphor plates have the benefit of a better thermal conductivity. In addition, new concepts for colour conversion, like the full phosphor conversion [47,48,50] may also reduce the impact of variations of the excitation wavelength. Nonetheless, from the above mentioned discussion it becomes obvious that even for these advanced technologies the constancy of the optical properties has to be guaranteed within a similar order of magnitude. Therefore, even if these concepts will become the common colour conversion technologies of the future, there still will be also an inevitable need for new phosphor materials in particular targeting on batch to batch reproducibility as well as temperature and long-term chemical stability of their optical properties in the low single-digit percent range.

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