

Optical Analysis of Down-Conversion OLEDs

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ABSTRACT

Phosphor down-conversion of blue organic light-emitting diodes (OLEDs) is one approach to generate white light, which offers the possibility of easy color tuning, a simple device architecture and color stability over lifetime. In this article previous work on down-conversion devices in the field of organic solid state lighting is briefly reviewed. Further, bottom emitting down-conversion OLEDs are studied from an optical point of view. Therefore the physical processes occurring in the down-conversion layer are translated into a model which is implemented in a ray tracing simulation. By comparing its predictions to experimental results the model is confirmed. For the experiments a blue-emitting polymer OLED (PLED) panel optically coupled to a series of down-conversion layers is used. Based on results obtained from ray tracing simulation some of the implications of the model for the performance of down-conversion OLEDs are discussed. In particular it is analysed how the effective reflectance of the underlying blue OLED and the particle size distribution of the phosphor powder embedded in the matrix of the down-conversion layer influence extraction efficiency.

Keywords: Organic light-emitting diode, OLED, ray tracing, simulation, phosphor, down-conversion

1. INTRODUCTION

The generation of white light by means of down-conversion is achieved by combining a blue-emitting light source and one or more luminescence converting materials, also termed as phosphors. Phosphors absorb a fraction of the photons emitted by the light source and re-emit them at longer wavelengths. The non absorbed fraction of the photons and the photons re-emitted by the luminescence converting material(s) constitute the light emitted by the device. The appropriate amount of phosphor material has to be used to achieve the color balance for the resulting white light aimed at. Therefore the material is embedded in a transparent matrix which is applied directly on the light source or constitutes a part of the device-housing.

Generation of white light by down-conversion offers significant advantages in comparison to other approaches^{1,2}, where two or more emissive components provide white light. Down-conversion devices offer better color stability as the aging rate is determined by only one emitter. The approach leads to a less complex architecture of the light source and thus can be implemented by easier fabrication techniques due to the presence of one single emitting component. Furthermore, the emission color can be controlled by adjusting the down-conversion layer without affecting the electrical properties of the underlying OLED.

Comparing the resulting efficiency of a down-conversion device to the efficiency of the underlying blue light source, the Stokes-shift due to the wavelength conversion, and the finite quantum yield of the phosphor material affect the resulting efficiency negatively. However, the photometric efficiencies (power efficiency [lm/W] and current efficiency [cd/A]) might be increased: In many cases the converted light is related to wavelengths corresponding to a higher sensitivity of the human eye.

Schlottter *et al.*³ were the first who introduced the down-conversion concept into solid state lighting technology. In 1997 they demonstrated inorganic white light emitting diodes (LEDs) comprising blue emitting GaN/6H-SiC chips as primary light sources and YAG:Ce³⁺ as luminescence converting material. The YAG:Ce³⁺ particles were embedded in the epoxy resin used for the dome of the LED.

Organic white light-emitting devices based on phosphor down-conversion are focus of the present article. At first a brief survey of previous work on down-conversion OLEDs is given. Then the physical processes in a down-conversion device and their translation into a ray simulation are outlined. Finally some of the implications of the model are discussed with regard to the optimization of external device efficiency.

2. PREVIOUS WORK ON DOWN-CONVERSION OLEDs

In 1997 Leising *et al.* introduced the down-conversion concept into OLED technology ^{4,5}. They demonstrated the realization of red, green, blue (RGB) light emission for display applications by covering a blue emitting OLED based on parahexaphenyl (PHP) (peak wavelength 425 nm) with color-converting dye/matrix layers. The blue emission was converted into green light by applying a thin film of coumarin in a poly-methyl-methacrylate (PMMA) matrix atop the OLED. The coumarin absorption spectrum efficiently overlaps with the PHP emission spectrum, so that the blue OLED emission can be efficiently absorbed and green photoluminescence re-emitted (peak 506 nm). For red light emission, a perylene dye (BASF Lumogen F300) in a PMMA matrix placed over the green emitting layer was used to absorb green light and re-emit in the red visible spectrum (peak wavelength 607 nm). Thereby Leising *et al.* achieved 90 % quantum efficiency for blue to green conversion and 80 % for blue to red conversion.

In 2002 Duggal *et al.* presented an OLED-device based on the down-conversion concept, which offers illumination quality white light emission ⁶. The white device consisted of a blue light-emitting polymer OLED (performance: current efficiency of 3.03 cd/A, power efficiency of 1.73 lm/W at 5.5 V) and of a series of three down-conversion layers applied on the reverse side of the glass substrate. The layers were comprised of BASF Lumogen F perylene orange in PMMA, BASF Lumogen F perylene red in PMMA and particles of YAG:Ce³⁺ in a poly-dimethyl siloxane silicone matrix. The output spectrum of the resulting white device corresponded to a color temperature of 4130 K on the blackbody locus and a color rendering index of 93. At 5.5 V the white device exhibited a brightness of 1080 cd/m² and a power efficiency of 3.76 lm/W. Duggal *et al.* showed that the use of the down-conversion phosphor system led to an overall power efficiency increase, an effect attributed to the high quantum efficiency of the luminescent converting materials and to the presence of light scattering in the phosphor layer. Using the same down-conversion layer system and a more efficient blue light-emitting polymer OLED (performance: 10 lm/W), Duggal *et al.* presented a 2ft x 2ft large area white OLED panel with a power efficiency of 15 lm/W and a total output of 1200 lm in 2005 ⁷. The white emission corresponded to CIE-coordinates of x/y = 0.36 / 0.36 (Color Temperature 4400 K) and a color rendering index of 88.

In 2006 A. Mikami proposed a new structure for down-conversion OLEDs ⁸. In this structure an orange emitting color-conversion layer (CCL) was regularly patterned at constant intervals on the substrate. Deep blue light emissive pixels were closely prepared around the CCL dots. The pixels were based on a polymer-small molecule hybrid OLED incorporating a fluorescent blue emitter. The pixel pitch of a unit cell including a blue OLED and a CCL-dot was in the range of 70~300 μ m. Thereby the lateral emission from the blue-light emitting layer could be efficiently transferred to CCL by optimizing the lateral propagation of light (SCM – Side-Coupling Color-Conversion Method). In comparison to the sole deep blue emitting OLED, the external quantum efficiency of the white emitting down-conversion device was improved from 5 % to 9 %. The device offered a power efficiency of 9.1 lm/W and its white emission was related to CIE color coordinates x/y = 0.35 / 0.26.

Another concept for down-conversion OLEDs was presented by Li *et al.* in 2007 ⁹. They demonstrated a novel structure of white small molecule OLEDs composed of a greenish blue fluorescent emitting layer and a red fluorescent dye-doped hole injection layer of 340 nm thickness. Within the device a part of the greenish blue EL was absorbed by the red fluorescent dye in the thick hole injection layer and converted into red photoluminescence (PL). The whole white emission from the device was a mixture of the greenish blue EL and red PL. The spectrum of the device (CIE x/y = 0.31 / 0.33) showed no change at a wide range of current density and during long-term continuous operation. In general, the use of a greenish blue EL component in a down-conversion device offers two remarkable advantages ¹⁰: First, greenish blue emitting systems are usually more stable than blue emitting systems. Second, in many cases a lower operating voltage can be achieved when comparing a down-conversion device based on blue/green EL to a white emitting device based on a stack incorporating three EL components. This is due to the absence of the red emitting component which often acts as a deep charge carrier trap within the diode.

3. PHYSICAL PROCESSES IN THE DOWN-CONVERSION LAYER

Fig. 1 shows the basic physical processes which occur in the phosphor layer of a down-conversion device. These processes can be illustrated by following the optical pathways of different photons emerging from the active layers of the OLED into the substrate: A photon emitted by the blue OLED can be absorbed by the phosphor and re-emitted at a longer wavelength (photon A in Fig. 1). The re-emission of an absorbed photon holds off in the case of non-radiative decay of the excited state in the phosphor material (photon B). Photon C in Fig. 1 has reached the interface between

phosphor layer and air with an angle of incidence exceeding the critical angle and undergoes total internal reflection. The photon then impinges a phosphor particle and is back-scattered toward the interface. This time, the angle of incidence is less than the critical angle and the photon is transmitted across the interface. Photon D is back-scattered into the active layers of the OLED device. After reflection at the cathode, the photon is extracted into air. However, a photon which has been back-scattered into the active layers can be absorbed by the organic layers or by the electrodes (photon E).

The complex refractive index of the phosphor material, the refractive index of the matrix of the down-conversion layer and the phosphor particle size distribution determine the average behaviour of photons impinging at phosphor particles. This behaviour is described by the average absorption and scattering cross section of the phosphor powder as well as by the corresponding scattering function. The scattering function $p(\lambda, \theta)$ is the probability function of the scattering angle, which is defined as the angular difference between the original and the new propagation direction of a light ray (wavelength λ) after it has been scattered by a phosphor particle. The average particle size of typical garnet phosphors is in the magnitude of order of a few microns. In this range the description of scattering and absorption is given by MIE-theory. The incidence of an electromagnetic plane wave onto a dielectric sphere is considered in this model¹¹.

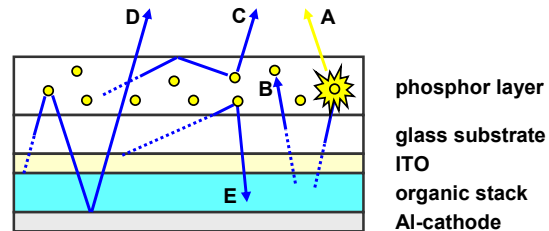


Fig. 1. Physical processes in the down-conversion layer: (A) absorption and re-emission by a phosphor particle, (B) absorption by a phosphor particle and non-radiative decay of the excited state in the phosphor material, (C) scattering by a phosphor particle leading to photon extraction into air, (D) reflection at the cathode, (E) absorption in the active layers of the OLED.

The solution of the MIE-theory shows that in the case of small spheres the whole sphere oscillates as a single dipole. The oscillation takes place symmetrically to the direction of wave incidence. Additional oscillations of multipoles occur considering larger spheres. With increasing particle size the superposition of the partial waves leads to a more and more complex spatial distribution with an increasing number of maxima and minima. Thereby the fraction of radiation scattered to the backward half-space decreases in comparison to the fraction of radiation scattered into the front half-space. The spatial distribution as a function of θ , which results from the superposition of all partial waves corresponds to the scattering function.

4. RAY-TRACING SIMULATION OF DOWN-CONVERSION OLEDs

The physical processes in the down-conversion layer were translated into a ray-tracing simulation. Simulations were performed using the Monte-Carlo-based ray-tracing software *Light Tools* obtained from Optical Research Associates¹². This software allows defining geometric objects in a three dimensional space. The optical properties of the bulk of these objects (i.e. refractive index and transmission) and of their surfaces (for example the reflectivity of a surface) can be set to simulate ray paths of light as they traverse through and within the objects according to geometrical ray optics. A light source related to a user-defined angular emission characteristic and emission spectrum can be placed within the objects. The wavelength and the propagation angle of a light ray emitted by the light source are determined by the Monte-Carlo-method (i.e. the emission spectrum and the angular emission characteristic are interpreted as probability distributions). The software is capable to simulate scattering and absorption/re-emission processes at luminescence converting particles randomly distributed in the bulk of a geometric object. Here a mean free pathway *MFPW* defines the average distance between two impingements at phosphor particles. The software varies the distance between two impingements randomly, while the average distance is kept equal to the set mean free pathway *MFPW*. The flow chart of the phosphor model of *Light Tools* is shown in Fig. 2. When a ray reaches a phosphor particle, the probability for its absorption is given by $P_{abs}(\lambda)$. The set quantum yield QY determines the re-emission of the absorbed light. The normalized re-emission spectrum of the phosphor as a function of wavelength is given by $S_c(\lambda)$. The angular distribution of the re-emitted light is isotropic. In the case of light scattering at a particle, the scattering angle is defined as the angular difference between the original and the new propagation direction of a light ray. For each single scattering event, the set scattering function $p(\lambda, \theta)$ determines the new propagation direction of the light ray.

The quantum yield of the phosphor and the ratio between absorption and scattering are interpreted by probabilities. Accordingly, the normalized spectral distribution of the blue OLED $S_{OLED}(\lambda)$, the isotropic re-emission of the phosphor particles, the scattering function $p(\lambda, \theta)$ and the normalized re-emission spectrum of the phosphor $S_c(\lambda)$ are interpreted by probability distributions. This allows simulating the corresponding physical processes by means of the Monte-Carlo-method.

The rays simulated by *Light Tools* can be analysed by using so-called receivers, which count the number of rays hitting at a certain user-defined surface. A far field receiver surrounds the objects traversed by the rays in infinite distance. Therefore, this receiver counts all the rays leaving the considered geometrical structure into the ambient. Furthermore, the far field receiver is capable to count rays in certain ranges of solid angle and the corresponding spectral distribution of the rays within this ranges. This allows analysing the emission color of the simulated system as a function of viewing angle.

In translating the physical structure of a down-conversion OLED to the ray-tracing simulation the down-conversion layer is represented by a cuboid (Fig. 3). This cuboid has the refractive index n_{matrix} . Scattering, absorption and re-emission by the particles in the down-conversion layer are simulated according to the phosphor model of *Light Tools*. Here the mean free path way $MFPW$ between two impingements at particles is given by

$$(Eq. 1) \quad MFPW = 1/N \cdot 1/q_{geo},$$

where N is the phosphor particle density in the down-conversion layer and q_{geo} is the average geometric particle cross section.

In a real device, light generated by the OLED enters the down conversion layer at its interface to the substrate. In the model, an area light source with angular distribution of photon emission $D(\alpha)$ ($0^\circ < \alpha < 90^\circ$) is placed at the bottom side of the cuboid representing the down-conversion layer. This distribution corresponds to the angular distribution of emission in the substrate of a real OLED. The normalized spectral distribution of this light source is given by $S_{OLED}(\lambda)$. The OLED layers are represented by one single layer forming the bottom of the cuboid. This layer has the reflectance $R_{OLED}(\lambda)$, which is the effective reflectance of the active layers as a function of wavelength. In the model, this reflectance $R_{OLED}(\lambda)$ is set to be independent from the angle of incidence.

On the top side of the cuboid, the critical angle for total internal reflection at the interface between down-conversion layer and air acts as the criterion of photon extraction into the ambient. According to Snell's law, the critical angle is given by

$$(Eq. 2) \quad \alpha_{crit}(\lambda) = \sin^{-1} (1/n_{matrix}(\lambda)).$$

The flowchart in Fig. 4 outlines the simulation of the propagation of a photon in the down-conversion layer in order to summarize the model as described above.

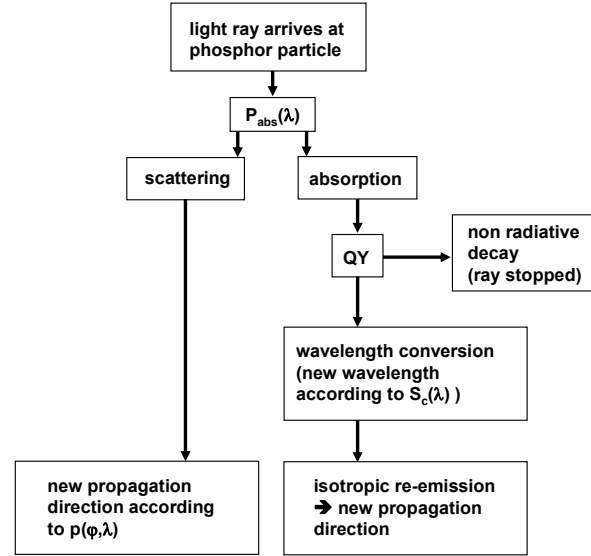


Fig. 2. Phosphor model in the simulation software Light Tools.

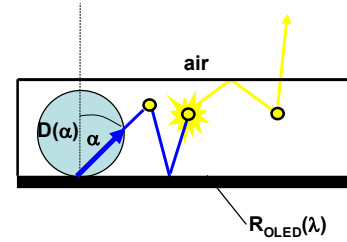


Fig. 3. Schematic illustration of the ray-tracing model of a down-conversion OLED. In the model, the OLED layers are grouped into a single layer.

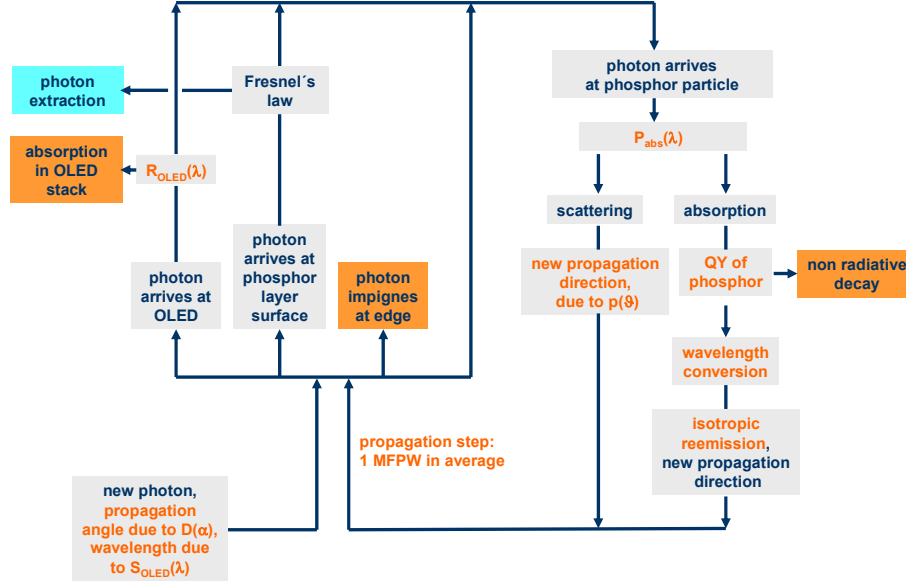


Fig. 4. Flow chart of the simulation based on the proposed model. All processes simulated by the Monte-Carlo-method are printed in red letters.

In this ray-tracing model of a down-conversion OLED, various simplifying approximations were made in effort to minimize and simplify the number of model input parameters. In particular, these approximations are:

- The OLED active layers are grouped into a single layer with the effective reflectance $R_{OLED}(\lambda)$. Hence in the model, the “light source” is a light emitting area, which is located at the bottom of the cuboide representing the down-conversion layer. The light source sends out light into the down-conversion layer in an angular distribution $D(\alpha)$.
- The effective reflectance of the OLED active layers $R_{OLED}(\lambda)$ is set to be independent from angle.
- The normalized spectral distribution of the light emitted by the blue OLED, $S_{OLED}(\lambda)$, is assumed to be independent from angle.
- All interfaces are considered to be planar.
- Substrate edge emission is neglected, i.e. all photons reaching the lateral border of the device are counted as absorbed.
- Absorption in the matrix material embedding the phosphor is neglected, i.e. the matrix material is regarded as completely transparent.

In the simulation, light in the range of wavelengths from 380 nm to 780 nm is considered in steps of 5 nm. The simulation software *Light Tools* allows computing the output spectra as a function of viewing angle by means of a far field receiver. The spectral distributions of photons leaving the conversion layer in certain ranges of solid angle with respect to the substrate normal are determined.

Furthermore, the far field receiver counts the number of rays leaving the down-conversion layer. The ratio between this number and the total number of rays emitted by the light source corresponds to the fraction of photons coupled into the substrate which is extracted into the ambient. Hence, in this consideration the total extraction efficiency of the device η_{ph} is decomposed into two components, i.e.

$$(Eq. 3) \quad \eta_{ph} = \eta_{OLED-s} \eta_{s-a} ,$$

where η_{OLED-s} is the fraction of the generated photons that is coupled into the substrate, and η_{s-a} is the fraction of photons coupled into the substrate which is extracted into the ambient. This decomposition is analogous to the distinction made between ITO/organic and substrate wave-guided modes and also analogous to the general method to evaluate substrate surface modification techniques proposed in reference¹³. Here the latter term is the primary focus. The effects of volumetric light scattering and phosphor absorption/re-emission upon the fraction of light emitted into the ambient, η_{s-a} , are considered in particular.

4. SAMPLE FABRICATION AND DETERMINATION OF MODEL INPUTS

In order to confirm the model, its predictions were compared to experimental results. Therefore a deep blue-emitting polymer OLED panel and two sets of down-conversion layers applied on free-standing glass substrates were fabricated. The sample fabrication and the measurements of the relevant physical properties of the OLED device are described in this section. Furthermore, the methodology aimed at obtaining the optical characterization of the phosphor is outlined.

4.1 Fabrication of the Blue OLED Panel

The blue emitting OLED panel had an active area of 4.2 cm x 3.3 cm (the dimensions of the OLED panel used in the experiments were set for the device geometry in the ray-tracing simulation). Additionally a smaller OLED (active area: 0.5 cm x 0.5 cm) with the same architecture (i.e. same layer thicknesses) was fabricated, which was necessary for the determination of the angular distribution of photon emission, $D(\alpha)$ (see below, paragraph "Emission Characteristics of the Blue OLED"). The OLED structure consisted of a glass substrate, 120 nm indium tin oxide (ITO), 120 nm poly(3,4)-ethylenedioxythiophene doped with poly(styrene sulfonate) (PEDOT:PSS), 80 nm deep blue light-emitting polymer and a Ba/Al cathode. The PEDOT:PSS was supplied by H.C. Starck. The organic layers were applied by spin-coating on ITO coated float glass substrate (refractive index $n_g = 1.52$). The cathode was applied by thermal evaporation through a shadow mask in a vacuum chamber under standard conditions. Deposition of the OLED stack was followed by encapsulation with a glass lid.

4.2 Fabrication of Down-Conversion Layers

A silicone was used as matrix material of the down-conversion layer. The refractive index of the silicone n_{matrix} was close to the refractive index of the OLED substrate ($n_g = 1.52$) and it had a transmission of 98 % through a sample of 1 mm thickness within the range of the visible spectrum. YAG:Ce³⁺ phosphor (yttrium aluminum garnet doped with cer, quantum yield of luminescence conversion $QY > 0.95$) obtained from OSRAM GmbH was used as luminescence converting material. By means of both a two axis rotary high-speed mixer and a masticator, the phosphor particles were thoroughly dispersed in the silicone matrix. This mixture was then applied on a glass substrate by means of the doctor blade technique using an Elcometer 4340 Film-Applicator. The thickness of the film was controlled by adjusting the gap between the doctor blade and the substrate. The film was cured 60 min at 150 °C. Two sets of films were fabricated this way. The first set (samples A1-5) had a phosphor concentration of 15.3 percent by volume, the second set (samples B1-4) a concentration of 20.3 percent by volume. The final thickness of the down-conversion layer was determined by a tactile thickness measuring gage (KLA-Tencor P12) at three spots of each film. The layer thicknesses of the first set of films were 17, 23, 49, 71 and 102 μm (films A-1 to A-5), the thicknesses of the second set were 18, 23, 55 and 70 μm (film B-1 to B-4).

4.3 Emission Characteristics of the Blue OLED

The angular dependence of the OLED light output as it goes from the OLED layers into the substrate, cannot be measured directly due to refraction and total internal reflection at the interface between glass substrate and air. To determine $D(\alpha)$, the small OLED (active area 0.5 cm x 0.5cm) was coupled to the center of a glass hemisphere (diameter 25 mm) by using a refractive index matching gel (Norland Optical Adhesive NOA 68). The emitted light was probed as a function of angle (steps of 5°) from the hemisphere by a spectral camera Photo Research PR650. This geometry effectively makes the emission angle in glass equal to the emission angle in air. Hence, basically all photons hit the surface of the glass hemisphere at an angle of 90°. This allows the measurement of the OLED emission within the substrate at angles exceeding the critical angle of totally internal reflection between glass and air (Fig. 5)^{14,15}. As the result of the measurement, Fig. 6 shows the angular light output emitted by the blue OLED into the glass substrate. The spectra measured as a function of angle from the hemisphere, showed a blue shift from CIE x/y = 0.164/0.124 at 0° to CIE x/y = 0.162/0.042 at 70°; emission color and intensity as a function of angle are determined by the optical half-

cavity formed by the OLED stack. The integrated spectral distribution of emission within the substrate is depicted in the inset of Fig. 6. To obtain this integrated spectrum, the spectra as a function of angle were weighted with their contribution to the total light output and summed up. As input for the simulations, the distributions $D(\alpha)$ and $S_{OLED}(\lambda)$ (in photons) were derived from the data plotted in the graphs of Fig. 6.

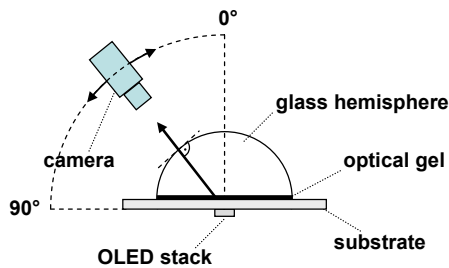


Fig. 5. Setup for the measurement of the angular distribution of OLED emission within the substrate.

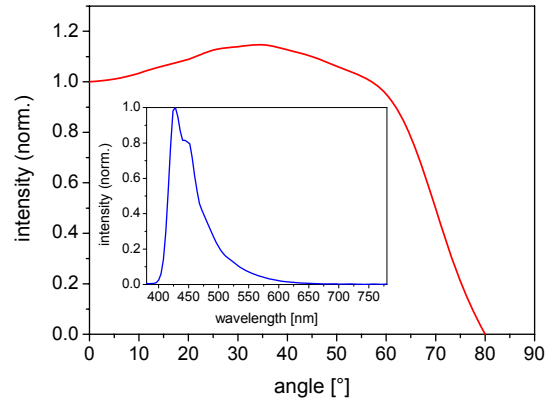


Fig. 6. Angular distribution of emission within glass substrate of the blue OLED. The inset shows the integrated spectral distribution of OLED emission within the substrate.

4.4 Effective Reflectance of the OLED Panel

The effective reflectance of the OLED panel $R_{OLED}(\lambda)$ was measured using a Perkin-Elmer reflectometer Lambda 950 at angles of 8°, 30° and 60° with respect to the substrate normal. The reflectance as a function of wavelength at the different angles is plotted in the graph in Fig. 7. In general, the resulting reflectance of a thin film structure depends on the angle of incidence due to interference effects. However, the measurements of the reflectance $R_{OLED}(\lambda)$ at 8°, 30° and 60° show a similar slope and differ only by 10 % at most. The low reflectance in the 400 nm wavelength region is given by the absorbance of the blue emitting polymer. At higher wavelengths, the effective reflectance of the OLED is mainly determined by the transmittance of the ITO anode and the reflectance of the aluminum cathode. Considering the minor variations in the measured angular reflectance, the effective reflectance is set to be independent from the angle of incidence in the simulation. The reflectivity at the angle of 30° is used as input for the simulations.

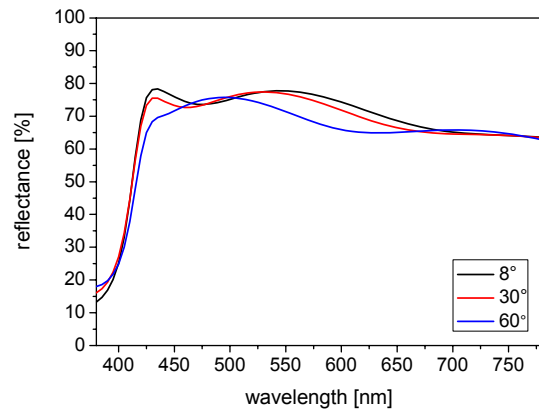


Fig. 7. The reflectance of the OLED-panel $R_{OLED}(\lambda)$ measured at angles of 8°, 30° and 60° with respect to the substrate normal.

4.5 Characterization of the Phosphor Powder

The behaviour of a photon impinging a phosphor particle is determined by the average scattering function, the average scattering cross section and the average absorption cross section. One needs knowledge about the refractive index of the embedding matrix, the complex refractive index of the phosphor and its particle size distribution for the MIE based computation of these characteristics. The particle morphology, on the other hand, is hardly of importance, since the statistic orientation of large amounts of non-spherical powder particles allows a description in terms of an “effective” particle size of spherical particles¹⁶.

The optical characterization of the YAG:Ce^{3+} powder used for the down-conversion layers was performed by OSRAM GmbH. First the phosphor particle size distribution was determined by a method utilizing sedimentation in a viscous gradient. The gradient was built inside a centrifuge. This way the determination of the particle size is conducted by measuring the time required to sink a defined distance. The determination of the complex refractive index of the YAG:Ce^{3+} powder used for the down-conversion layers was performed by an alternative approach to the direct experimental determination of the optical properties. The determination according to this method is conducted as follows¹⁶: First the re-emission spectrum of a powder plaque with a defined volume fill factor (in the range between 40 % and 50 %) was measured. The setup of the measurement was translated into a computer model. Literature values for the refractive index of the host lattice of the phosphor material (i.e. YAG for YAG:Ce^{3+}) and the particle size distribution determined as described above were used as input parameters for the simulation. A first curve progression for the imaginary component of $n_{phos}^*(\lambda)$ can be derived by applying the Kubelka-Munk function¹⁷ on the measurement of the powder reflectance. The simulation software computes the average scattering absorption cross section of the phosphor powder as well as the corresponding scattering function according to MIE-theory and simulates the behaviour of the powder plaque, i.e. the simulation gives a first re-emission spectrum. The first simulation result will most likely differ from the measured re-emission spectrum. By introducing physically reasonable absorption bands of various kinds, the complex refractive index is altered until the simulation fits the measurements sufficiently.

Based on the measurements of the particle size distribution, based on the complex refractive index of the phosphor (determined as described above) and based on the refractive index of the silicone used as matrix of the down-conversion layers (see appendix E), the average single scattering characteristics in silicone as surrounding medium were computed according to MIE-theory in the spectral range from 380 nm to 780 nm in steps of 5 nm. As a result of this computation, Fig. 8 shows the plot of the average scattering function $p(\vartheta)$ for wavelengths 420 nm, 530 nm, and 600 nm, and Fig. 9 shows the plot of the average absorption probability as a function of wavelength, $P_{abs}(\lambda)$, which is given by

$$(Eq. 4) P_{abs} = Q_A(\lambda) / (Q_A(\lambda) + Q_S(\lambda)),$$

where $Q_A(\lambda)$ is the average absorption cross section of the particle as a function of wavelength, and $Q_S(\lambda)$ is the average scattering cross section as a function of wavelength. Additionally, the phosphor luminescence spectrum is depicted in the inset of Fig. 9.

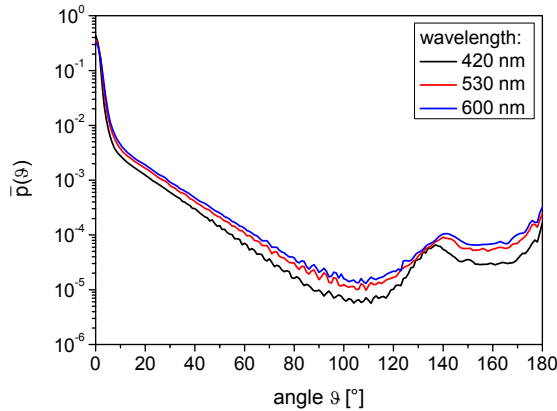


Fig. 8. Plot of the average scattering function $p(\vartheta)$ of the phosphor powder in silicone as the surrounding medium calculated for wavelengths 420 nm, 530 nm and 600 nm.

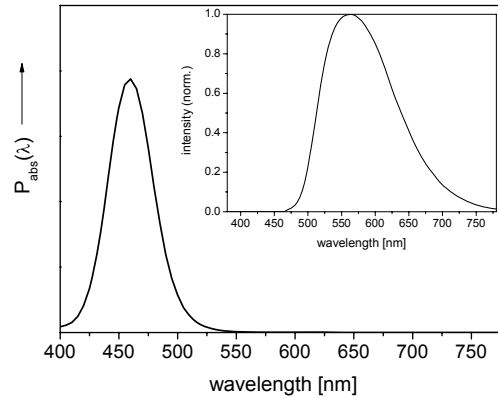


Fig. 9. Plot of the average absorption probability as a function of wavelength for silicone as the surrounding medium. The inset shows the luminescence spectrum of YAG:Ce^{3+} (excitation wavelength 460 nm). The data was obtained from OSRAM GmbH.

5. RESULTS AND DISCUSSION

5.1 Confirmation of the Model

The glass substrates carrying the down-conversion layers were optically coupled to the blue emitting OLED panel by using an optical gel (Norland Optical Adhesive 68, refractive index $n = 1.54$). The emission of the panel with and without down-conversion layers was measured as function of the angle with respect to the substrate normal. The emission was probed by a Photo Research PR650 spectral camera in steps of 10° . All measurements were carried out at a fixed current of 20 mA. While performing the measurements, it was confirmed that there was no decrease in the light output of the OLED-panel caused by degradation processes in the active layers.

5.1.1 Output Spectrum

Fig. 10 shows the integrated spectrum of the down-conversion device comprising the blue panel and layer A3 as derived from measurements. To obtain this integrated spectrum, the spectra measured as a function of viewing angle were weighted with their contribution to the total light output and summed up. Furthermore, the corresponding integrated spectrum obtained from simulation is depicted in Fig. 10. In the simulation, the extracted photons were collected by means of the far field receiver. There is good agreement in the slopes of both spectral distributions.

Additionally, Fig. 11 gives an overview of the CIE-coordinates related to the integrated spectra, which were obtained from simulation and measurements of all conversion layers used in this study. The graph proves the good agreement between simulation and experimental results in a broad range of conversion layer thickness.

Next, the output spectrum as a function of viewing angle is considered. The CIE-coordinates corresponding to the measured angular emission of the blue panel combined with layer A3 are shown in Fig. 12a. A yellow shift in the light output is observed, when the viewing angle is increased. The corresponding simulation results (Fig. 12b) reproduce the same effect. This effect can be explained when considering photons which are generated by the OLED and coupled into the glass in different angles with respect to the substrate normal (Fig. 13). With increasing angle, the average optical path of a photon through the conversion layer into the ambient becomes longer, i.e. the probability of a photon being absorbed by the phosphor increases. Consequently, the probability of a photon leaving the conversion layer without being absorbed by the phosphor increases with decreasing propagation angle, which in turn leads to a more bluish emission at small viewing angles.

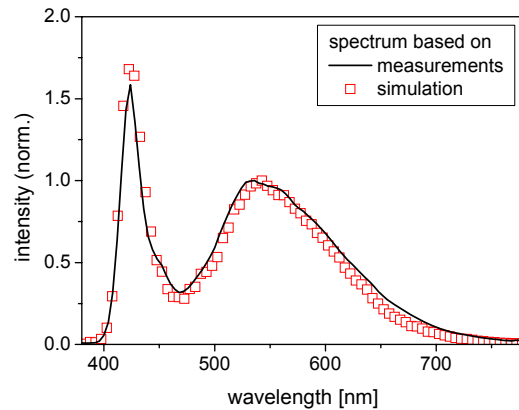


Fig. 10. Integrated spectrum based on measurement in comparison to the simulation result for the blue panel equipped with the conversion layer A3.

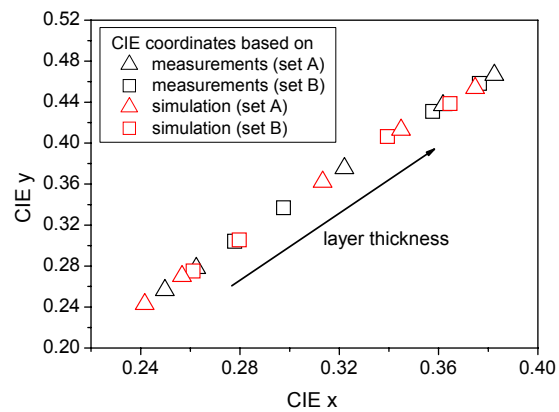


Fig. 11. Plot of the CIE-coordinates related to the integrated spectra, which were obtained from simulations and measurements for all conversion layers used in this study.

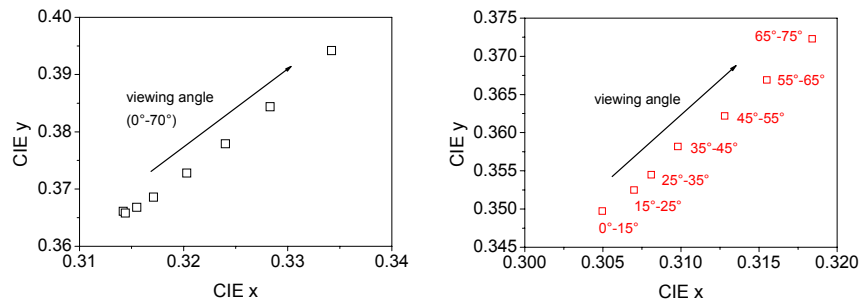


Fig. 12. Color coordinates of the light output as a function of viewing angle based on (a) measurement and (b) simulation for the blue panel equipped with down-conversion layer A3. The color coordinates in the graph of Figure (b) correspond to spectral distributions of simulated photons leaving the conversion layer in certain angular ranges with respect to the substrate normal.

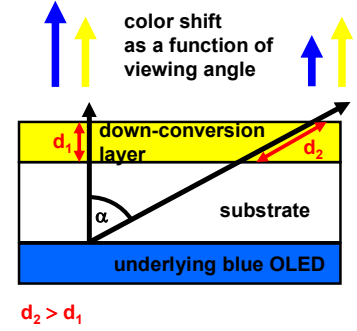


Fig. 13. The color shift is due to the difference in the average optical path length through the conversion layer of photons coupled into the substrate in different angles.

5.1.2 Extraction Efficiency

After applying the down-conversion layer A3 atop the blue OLED panel, the device appeared not only white (CIE $x/y = 0.32/0.37$) but also much brighter. The luminous intensity measured in the direction of the substrate normal at 20 mA increased by a factor of 3.4 from 42 cd/m^2 to 141 cd/m^2 . This effect may be attributed to the higher sensitivity of the human eye at wavelengths related to yellow light than at wavelengths related to blue light. The white spectrum (Fig. 14) has been fitted according to a down-conversion model proposed by Duggal *et al.*⁶. The fit allows the calculation of the conversion factor, which is the ratio of blue to expected white luminous efficiency. This calculation of the expected efficiency includes parameters related to the sensitivity of the human eye, the quantum yield of the phosphor and the Stokes shift between the energy of absorbed and re-emitted photons. The conversion factor obtained by the fit is $c = 2.5$, far lower than the increase in luminous intensity by a factor of 3.4 seen experimentally.

This difference should be attributed to light extraction enhancement due to light scattering by the phosphor particles, which is not considered by the model proposed by Duggal *et al.*

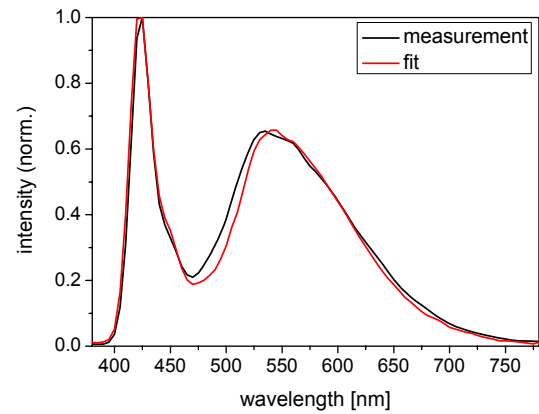


Fig. 14. Emission spectrum of the blue panel equipped with down-conversion layer A3 and its fit according to the model of Duggal *et al.*

The values of photon extraction efficiency η_{s-a} (see Eq. 3) for the blue panel equipped with the different down-conversion layers used in this study were determined for a more detailed analysis of light outcoupling. In this consideration, the extraction efficiency η_{s-a} of the blue OLED panel without conversion layer is set to be equal to the one of the smaller $0.5 \text{ cm} \times 0.5 \text{ cm}$ OLED which has the same structure as the panel regarding materials and layer thicknesses. Here, an extraction efficiency of $\eta_{s-a} = 0.44$ was derived by comparing the total light output obtained from the angular measurements of the emission with glass hemisphere to the one measured without glass hemisphere. Having in mind that the fraction of the generated photons coupled into the substrate, η_{OLED-s} , is not influenced by the down-conversion layer (i.e. $\eta_{OLED-s} = \text{constant}$), the extraction efficiency η_{s-a} for the blue panel equipped with a down-conversion layer can be derived from the measurements as follows:

$$(Eq. 5) \quad \eta_{ph}(blue) = \eta_{OLED-s} \eta_{s-a}(blue)$$

$$(Eq. 6) \quad \eta_{ph}(dc) = \eta_{OLED-s} \eta_{s-a}(dc)$$

$$(Eq. 7) \quad \rightarrow \eta_{s-a}(dc) = \eta_{s-a}(blue) (\eta_{ph}(dc) / \eta_{ph}(blue)) = \eta_{s-a}(blue) (O(dc) / O(blue)),$$

where $\eta_{ph}(blue)$ is the total extraction efficiency of the blue panel (see Eq. 3); $\eta_{s-a}(blue)$ is the fraction of photons coupled into the substrate of the blue panel, which is emitted into the ambient; $\eta_{ph}(dc)$ is the total external efficiency of the blue panel equipped with the down-conversion layer; $\eta_{s-a}(dc)$ is the fraction of photons coupled into the substrate, which is emitted through the substrate and the conversion layer into the ambient (converted and non-converted photons); $O(blue)$ is the output of the blue panel (in photons) obtained from measurements of angular emission, and $O(dc)$ is the output of the blue panel equipped with the conversion layer (in photons) obtained from measurements of angular emission.

Fig. 15 shows the extraction efficiency versus the film thickness as determined, based on both measurements and simulations for both sets of down-conversion layers. The data was brought together into one graph by introducing the product of the layer thickness and the phosphor volume concentration, henceforth termed as *normalized layer thickness*, as magnitude for the axis of abscissae. The data presented in Fig. 15 can be described using a simple physical picture^{18,19}. In the plot based on measurements as well as in the plot based on simulation results, there is a value of normalized layer thickness related to a maximum in light extraction, which is 61 % as determined by measurements and 63 % in the simulations. At lower values, wave-guiding within the substrate is not efficiently suppressed by scattering at the phosphor particles (see Fig. 1, photon C), while at higher values, more and more light is back-scattered into the OLED stack leading to absorption losses (see Fig. 1, photon E). The peak value is the point where these two effects are balanced. Minor losses slightly increasing with layer thickness are caused by the finite quantum yield of the phosphor.

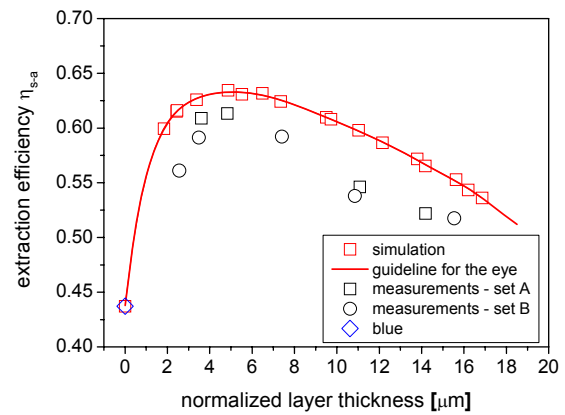


Fig. 15. Extraction efficiency as a function of layer thickness for the blue panel equipped with the layers of set A (a) and the layers of set B (b). The data for both sets are brought together into one graph by introducing the normalized layer thickness.

There is good agreement between model prediction and experimental data, i.e. the slope of both plots is very similar and the location of the maximum in light extraction agrees. The extraction efficiencies predicted by simulation are slightly higher than the experimental data. These minor differences could be caused by setting the effective OLED reflectance, $R_{OLED}(\lambda)$, to be independent from the angle of incidence, which might lead to an overestimation of $R_{OLED}(\lambda)$ in the simulation. Furthermore, differences in the thicknesses of the active layers between the blue panel and the 0.5 cm x 0.5 cm OLED could lead to deviations in the location of the emission zone and, consequently, to deviations in the corresponding angular photon distributions $D(\alpha)$ (which is determined by the position of the emission zone in the thin film stack). This could be a reason for an error in the extraction efficiency $\eta_{s-a}(blue)$ assumed for the blue panel, which in turn could affect the extraction efficiencies determined according to Eq. 7.

5.2 Influences on Extraction Efficiency

In the previous sections, a model of a down-conversion OLED has been developed and experimentally confirmed. Some of the implications of this model for the performance of such devices are discussed in the following. In particular, it is analysed how the effective OLED reflectance and the phosphor particle size distribution influence extraction efficiency. Thereby, room for improvement and challenges in the design of down-conversion OLEDs are identified.

5.2.1 Influence of OLED-Reflectance on Extraction Efficiency

Due to wave-guiding, back-scattering and isotropic re-emission from the excited phosphor, a fraction of the photons propagating in the down-conversion layer re-enters the active layers of the OLED, where photons can be either absorbed or reflected back into the down-conversion layer. Thus, the extraction efficiency of a down-conversion device relies on the effective reflectance of the underlying OLED. To analyse the impact of the OLED reflectance, the extraction efficiency as a function of R_{OLED} has been computed using the proposed ray-tracing model. Here the extraction efficiency of the blue OLED panel equipped with the conversion layer A3 was determined. In the simulation, the reflectance of the panel as a function of wavelength was replaced by values of R_{OLED} that were set to be independent from wavelength and varied from 0 to 1.

The extraction efficiency is plotted versus the effective reflectance of the OLED in Fig. 16. As the reflectance increases, the extraction efficiency also increases. At higher values of reflectance the slope of the plot becomes steeper. For a standard bottom emitting OLED, $R_{OLED} \approx 0.8$ is a typical value for the effective reflectance¹⁸. In this region, a change in reflectance of a few percent has a significant impact on extraction efficiency. This interrelationship should be kept in mind when choosing materials for OLED stacks, on whose substrate surface down-conversion layers or scattering layers for light extraction enhancement are applied. For example, in comparison to aluminum, silver has a higher reflectivity and its use as cathode material offers room for improvement in extraction efficiency. For high values of R_{OLED} , η_{s-a} can be nearly unity, i.e. very efficient “photon recycling” occurs. Intuitively, this is expected since, in the absence of absorption losses in the active layers, a given photon can impinge upon the interface many times until it escapes. As a result of the simulations mentioned above, the color coordinates related to the integrated spectra are given in Fig. 17. As the reflectance increases, the color of device emission is shifted from bluish white to greenish/yellowish white. This effect can be explained by considering the isotropic re-emission of the phosphor. Half of the converted photons (related to wavelengths in the yellow range of the visible spectrum) are re-emitted towards the OLED stack where the absorption losses occur. However, at higher values of reflectivity, the probability of photons being reflected into the conversion-layer and being extracted into air increases. Consequently, the emission color of a down-conversion OLED is not only determined by the thickness of the down-conversion layer but also by the effective device reflectance, i.e. when applying similar down-conversion layers on two OLEDs with the same spectral distribution of emission, the resulting output spectra may vary if the stacks differ in reflectance.

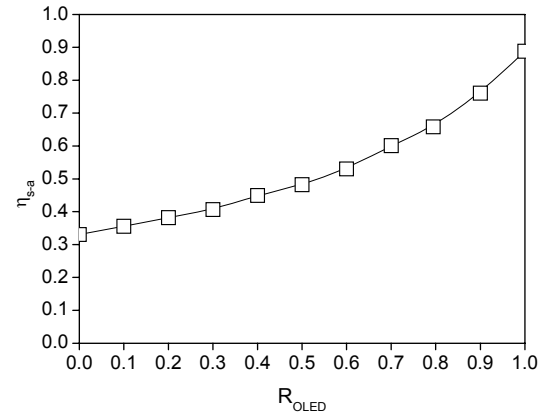


Fig. 16. Extraction efficiency as a function of effective OLED reflectance obtained by ray-tracing simulation.

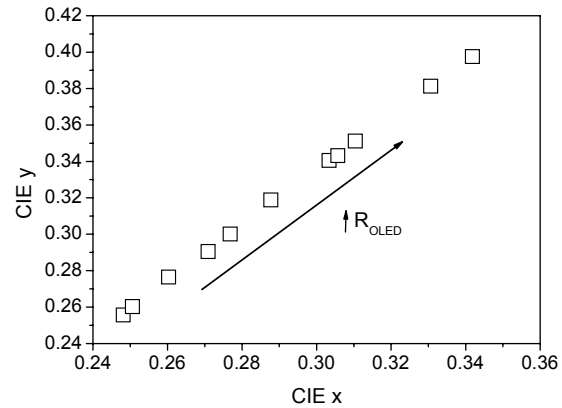


Fig. 17. CIE-coordinates related to the emission of the simulated down-conversion device as a function of OLED reflectance.

5.2.2 Role of the Phosphor Particle Size Distribution

In the presented ray-tracing model, the behaviour of photons impinging particles in the down-conversion layer is given by the average absorption cross section, by the average scattering cross section and by the scattering function related to the phosphor powder. These characteristics are determined by the particle size distribution of the phosphor powder. In contrast to the analysis of extraction efficiency as a function of effective OLED reflectance, the complex influence of the

phosphor particle site distribution on resulting device efficiency of down-conversion OLEDs can hardly be estimated without modelling.

To investigate the effect of phosphor particle size distribution on extraction efficiency, four distributions of YAG:Ce³⁺ particle size ($\nu_1(D)$, $\nu_2(D)$, $\nu_3(D)$, $\nu_4(D)$) are considered. Distributions as $\nu_1(D)$ and $\nu_3(D)$ can be obtained by the technical phosphor-annealing process and subsequent milling of the powder. Here $\nu_3(D)$ is the particle size distribution of the phosphor powder used in the experiments presented in section 5.1. The distributions $\nu_2(D)$ and $\nu_4(D)$ are derivatives of $\nu_1(D)$ and $\nu_3(D)$, respectively, and represent powders as they would be received from an ideal classification process: Distribution $\nu_2(D)$ was derived by removing all particles smaller than a certain diameter D_1 from distribution $\nu_1(D)$; distribution $\nu_4(D)$, accordingly, was derived by removing all particles smaller than a certain diameter D_2 from distribution $\nu_3(D)$. The average particle size increases from distribution $\nu_1(D)$ to distribution $\nu_4(D)$. For each of the distributions $\nu_1(D)$, $\nu_2(D)$, $\nu_4(D)$, the average scattering cross section, the average absorption cross section and the corresponding scattering function in the silicone used for the down-conversion layers as surrounding medium were computed according to MIE-theory. As a result of this computation, Fig. 18 summarizes the absorption probability at wavelength 460 nm. The scattering functions associated to the distributions are plotted in Fig. 19 a-d exemplarily for wavelengths 420 nm, 530 nm, and 600 nm.

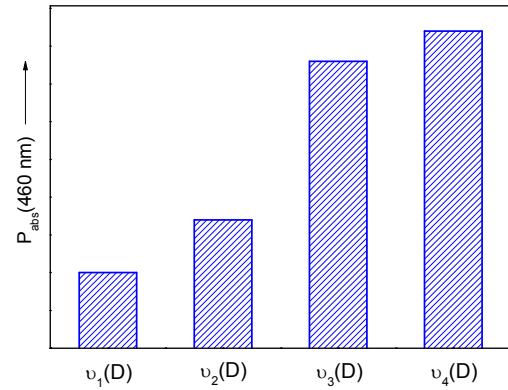


Fig. 18. Absorption probability $P_{\text{abs}}(460\text{nm})$ at wavelength 460 nm for the four considered distributions of phosphor particle size (surrounding medium: silicone).

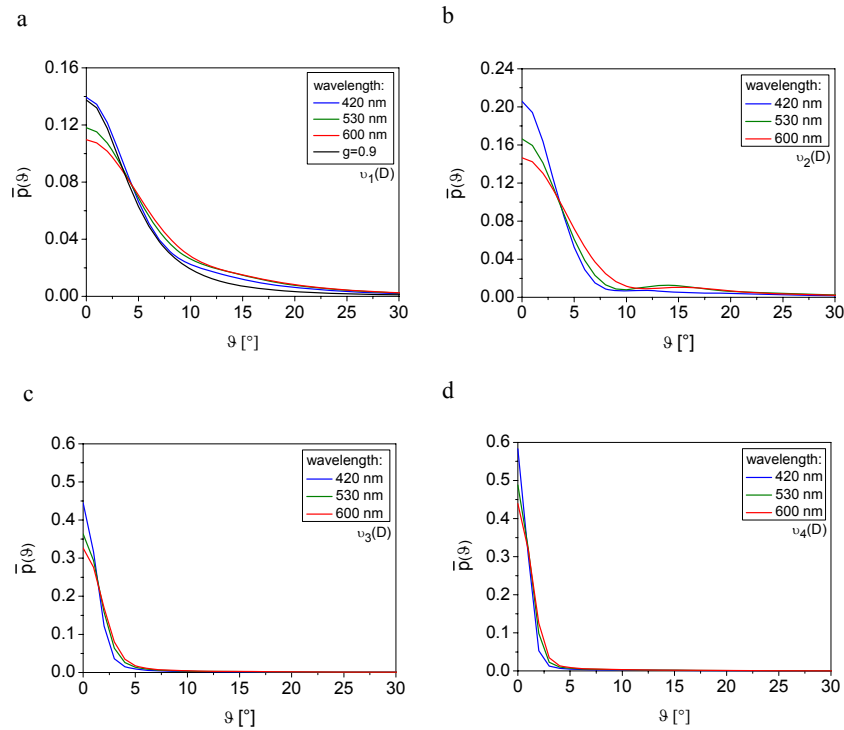


Fig. 19. Linear plots of the scattering functions in silicone corresponding to the YAG:Ce³⁺ phosphor particle size distributions $\nu_1(D)$, $\nu_2(D)$, $\nu_3(D)$, $\nu_4(D)$ (derived according to MIE- theory). In (a) the Henyey-Greenstein function related to $g = 0.9$ is plotted (black line).

As already performed in the case of distribution $\nu_3(D)$, the extraction efficiency as a function of normalized layer thickness was simulated for devices which comprise the blue PLED panel and down-conversion layers containing YAG:Ce³⁺ powders with particle size distributions $\nu_1(D)$, $\nu_2(D)$, $\nu_4(D)$. Here, in the ray-tracing simulation, the model inputs characterizing the underlying OLED were the same as used in section 5.1. The results are depicted in Fig. 20. Additionally, the dependence of extraction efficiency on normalized layer thickness for the case of the distribution $\nu_3(D)$ is plotted in Fig. 20, which has already been presented in section 5.1.2.

For each particle size distribution, the computed extraction efficiency η_{s-a} , as a function of layer thickness, has the same characteristic slope already discussed in chapter 5.1.2, i.e. initially η_{s-a} increases as the layer thickness is increased, then η_{s-a} reaches a maximum value and decreases as the layer thickness is further increased. With increasing average particle size the corresponding peak value decreases from 0.67 to 0.61.

The computed dependence of the extraction efficiency on particle size and on normalized layer thickness, respectively, is related to results published by Bathelt *et al.*^{20,21}. They investigated light extraction enhancement by volumetric light scattering in diffuse layers applied on the substrate surface. The diffuse layers comprised hollow polymer particles embedded in a transparent acrylate matrix. Bathelt *et al.* developed a ray-tracing model that quantifies the effect of light scattering on the output of bottom emitting OLEDs. In this model, the scattering function of the particles embedded in the diffuse layer is given by the Henyey-Greenstein scattering function. Here the effect of the particle size is contained in a single parameter g (see appendix D). This parameter g is the expectation value of the cosines of the scattering angle. Analogous to the data shown in Fig. 20 for each value of g , their model predicted a maximum in light extraction enhancement at a particular value of particle loading at a fixed layer thickness. The maximum enhancement of 1.4 was reached for particles related to g -factors in the range between 0.5 and 0.7. Higher and lower values of g led to less effective light extraction enhancement. Comparing the plot of the Henyey-Greenstein function to the average scattering functions corresponding to the four phosphor particle size distributions introduced above, each of the four scattering functions would be related to a g -factor $\geq \approx 0.9$. However, the deviation of scattered light from its original trajectory is more and more pronounced from distribution $\nu_4(D)$ to $\nu_1(D)$. Hence, the scattering function corresponding to distribution $\nu_1(D)$, for which the simulation predicts the highest extraction efficiency, is closest to the optimum scattering function proposed by Bathelt *et al.* for light extraction enhancement by diffuse layers.

Though there is similarity between the results of the analysis of light extraction enhancement by Bathelt *et al.* and the predictions of the model proposed within this work (i.e. similar curve progression of the extraction efficiency as a function of layer thickness/scatterance and same magnitude of order in reachable light extraction enhancement), major differences between both studies exist regarding the physical processes within the layers and the purpose of the considered substrate surface modifications: First of all, while in an ideal diffuse layer photons are only scattered by the embedded particles, in a down-conversion layer a fraction of the photons also undergoes *absorption and isotropic re-emission*. Furthermore, the primary purpose of a phosphor layer is the color conversion from blue to white. This leads to major challenges in translating the guidelines for efficiency enhancement published by Bathelt *et al.* to a down-conversion OLED. To illustrate this, values of η_{s-a} related to similar color coordinates in the white region (CIE $x/y = 0.32 / 0.38$) are marked with a circle in each curve of Fig. 20. Consequently, in this case the phosphor particle distribution $\nu_3(D)$ is most suitable for the efficient generation of white light. Here, according to simulation, an extraction efficiency of $\eta_{s-a} = 0.63$ can be reached, which was almost reached experimentally as shown in section 5.1. (see Fig. 15). While the extraction efficiencies related to $\nu_2(D)$ and $\nu_4(D)$ are in the same magnitude of order as the one corresponding to $\nu_3(D)$, the use of distribution $\nu_1(D)$ would lead to a white emitting device of significantly lower efficiency.

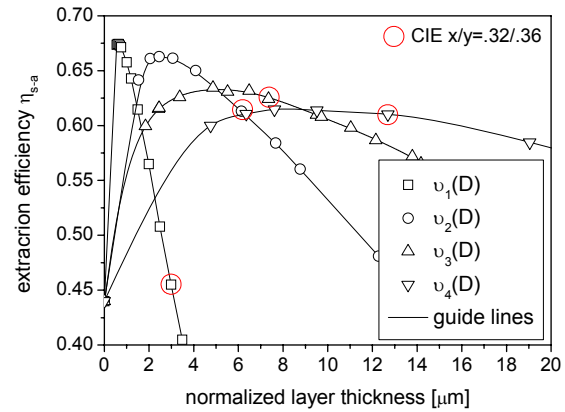


Fig. 20. Extraction efficiency η_{s-a} as a function of normalized layer thickness, which has been obtained by simulation for each of the considered phosphor particle size distributions. All data points related to similar color coordinates (CIE $x/y \approx 0.32/0.38$) are marked with a circle.

When optimizing diffuse layers for light extraction enhancement, there is complete freedom in the choice of appropriate layer parameters (layer thickness, particle loading and particle size). However, the optimization of down-conversion layers is restricted by the target color coordinates. In the optimum configuration, the fraction of photons, which is necessary to reach the target color coordinates, is converted by the layer and at the same scattering at the phosphor particles leads to efficient light extraction enhancement. For given target color coordinates, this balance is determined by the ratio between scattering and absorption within the layer, i.e. in terms of the ray-tracing model by the absorption probability (Fig. 18). The average absorption cross section and the average scattering cross section related to a given phosphor powder are magnitudes which are not only determined by the particle size distribution, but also by the complex refractive index of the phosphor material and by the refractive index of the surrounding matrix material. Considering these circumstances, it seems hardly possible to develop general design guide-lines for the optimum phosphor particle size (distribution). However, the presented results implicate a careful choice of the phosphor powder, since the particle size distribution has a significant impact on the resulting external device efficiency of white light-emitting down-conversion OLEDs.

Additionally, the use of nanoparticles²², of molecular dyes (for example perylene³) or of polymers^{23,24} as luminescence converting materials is discussed. The small size of these materials – significantly smaller than the wavelength of visible light – eliminates all light scattering. In LED technology, quantum dots are regarded as potential phosphors leading to an increase of device efficiency. According to reference²², the introduction of quantum dots could double external device efficiency in comparison to white LEDs based on conventional larger size phosphor powders which cause optical back scattering losses.

Contemplating a non-scattering phosphor, the only change in the propagation direction of light within the down-conversion layer is given by isotropic re-emission of the phosphor. Assuming a refractive index of $n_{matrix} = 1.5$ for the matrix material, the critical angle for total internal reflection at the interface to air is $\alpha_{crit} = \sin^{-1}(1/n_{matrix}) \approx 42^\circ$. Derived from geometrical considerations (Eq. 8 expresses the ratio between a spherical sector with an apex angle of $2\alpha_{crit}$ to the total sphere volume.), the fraction of re-emission within the escape cone in the direction towards the interface to air is given by:

$$(Eq. 8) \quad P_1 = 0.5 (1 - \cos \alpha_{crit}) \approx 0.13 \quad \text{for } \alpha_{crit} = 42^\circ.$$

Furthermore, light is re-emitted towards the OLED stack. The major part of the light incidence at the cathode is reflected back. Thus another fraction of the phosphor re-emission, P_2 , is extracted to air:

$$(Eq. 9) \quad P_2 = R_{OLED} \cdot P_1$$

The effective OLED stack reflectance of a typical bottom emitting OLED is $R_{OLED} \approx 0.8$ (i.e. $P_2 \approx 0.1$). Hence, $P_1 + P_2 \approx 0.23$ corresponds to the extraction efficiency η_{s-a} for the converted light. For comparison, the typical outcoupling efficiency from glass to air is $\eta_{s-a} \approx 0.5$ for an optimized conventional bottom emitting OLED with one emissive component (no substrate surface modification)¹⁴. Contemplating that the non-absorbed fraction of the blue OLED emission is not influenced by the phosphor, the external device efficiency is significantly reduced in comparison to the unmodified blue OLED.

Considering light extraction from a flat panel down-conversion OLED, the introduction of non-scattering phosphors is disadvantageous. However, if a reflecting off-state appearance of the device is desired, the use of non-scattering phosphors is indispensable. Scattering particles of a material non-absorbing in the wavelength region of visible light (Al_2O_3 for example) might be added, if a non-scattering phosphor is needed to obtain the output spectrum aimed at.

6. CONCLUSION

Previous work on down-conversion OLEDs has been reviewed. Furthermore down-conversion OLEDs have been studied from an optical point of view. Therefore the optical processes occurring in such devices were translated into a ray-tracing simulation. The methods to obtain all relevant model inputs have been demonstrated by a blue polymer OLED panel and a series of down-conversion layers comprising of $YAG:Ce^{3+}$ particles as phosphor. The simulation model has been confirmed experimentally by comparing its predictions derived from ray-tracing simulation to measurements. In agreement with previous work in the field, both experimental and simulation results have shown that the application of a phosphor layer on the substrate surface of an OLED can lead to an increase in photon extraction efficiency. Considering

the influence of phosphor concentration in the matrix and the influence of physical layer thickness on external device efficiency, a maximum in extraction efficiency occurs at a certain value of normalized layer thickness. At lower values of normalized layer thickness, wave-guiding within the substrate is not efficiently suppressed by scattering at the phosphor particles, while at higher values, more and more light is back-scattered into the OLED stack leading to absorption losses. The maximum value in extraction efficiency is given by the balance of these two effects.

However, the normalized thickness of the down-conversion layers is usually given by the target color coordinates of the resulting device. In the optimum configuration, the fraction of photons, which is necessary to reach the target color coordinates, is converted by the layer and scattering by the phosphor particles leads to efficient light extraction enhancement at the same time. This balance is given by the ratio between scattering and absorption at the phosphor particles. According to MIE-theory, the ratio between scattering and absorption probability depends on the phosphor particle size distribution. Using the ray-tracing simulation, the light extraction enhancement due to the phosphor layer has been studied for a set of different phosphor particle size distributions. The obtained results implicate a careful choice of the phosphor powder, since the particle size distribution has a significant impact on the resulting external device efficiency of white light-emitting down-conversion OLEDs. However, it seems hardly possible to develop general design guide-lines for the optimum phosphor particle size distribution, since in each case the target color coordinates and the optical constants of the phosphor material and its matrix have to be considered. But case studies for certain known phosphors are possible and will enable the build-up of efficient OLEDs offering the right spectral emission characteristics. The simulation model can also be transferred to the inorganic chip level conversion LEDs.

Additionally, the role of effective stack reflectance of the underlying blue OLED has been studied as a further influence on photon extraction efficiency of down-conversion OLEDs. To achieve optimum external device efficiency, the blue OLED should offer high effective stack reflectance. Ray-tracing simulation results show, that in the region of effective stack reflectance of typical bottom emitting OLEDs, a change in reflectance of a few percent has a significant impact on external device efficiency.

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[B. Hahn](#) ([/profile/Berthold.Hahn-28591](#)), [A. Weimar](#), [M. Peter](#), [J. Baur](#)

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[T. P. Chen](#) ([/profile/Tzer-Perng.Chen-12991](#)), [C. L. Yao](#), [C. Y. Wu](#), [J. H. Yeh](#), [C. W. Wang](#), [M. H. Hsieh](#) ([/profile/Ming-Ying.Hsieh-1553](#)).

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ORGANIC LEDs

Intrinsic OLED emitter properties and their effect on device performance ([/conference-proceedings-of-](#)

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LED FABRICATION AND MEASUREMENT

Novel approach for LED luminous intensity measurement ([/conference-proceedings-of-spie/6910/69100C/Novel-approach-for-LED-luminous-intensity-measurement/10.1117/12.760817.full](#))  Paper

Ron Rykowski ([/profile/Ronald.Rykowski-16267](#)), *Hubert Kostal* ([/profile/Hubert.Kostal-36497](#))

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GAN GROWTH

Secrets of GaN substrates properties for high luminosity of InGaN quantum wells ([/conference-proceedings-of-spie/6910/69100G/Secrets-of-GaN-substrates-properties-for-high-luminosity-of-InGaN/10.1117/12.755767.full](#))  Paper

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NOVEL LED STRUCTURE I

Comparison of numerical modeling and experiments of InGaN quantum wells light-emitting diodes with

SiO₂/polystyrene microlens arrays ([/conference-proceedings-of-spie/6910/69100M/Comparison-of-numerical-modeling-and-experiments-of-InGaN-quantum-wells/10.1117/12.763973.full](https://doi.org/10.1117/12.763973))  Paper

Yik-Khoon Ee ([/profile/Yik-Khoon.Ee-70710](https://doi.org/10.1117/12.763973)), *Pisist Kumnorkaew*, *Hua Tong* ([/profile/Hua.Tong-33328](https://doi.org/10.1117/12.763973)), *Ronald A. Arif* ([/profile/Ronald.Arif-60202](https://doi.org/10.1117/12.763973)), *James F. Gilchrist*, *Nelson Tansu*

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Improvement of light extraction from micro-pattern encapsulated GaN-based LED by imprinting

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Kui Bao ([/profile/Kui.Bao-90365](https://doi.org/10.1117/12.763285)), *Bei Zhang* ([/profile/Bei.Zhang-65239](https://doi.org/10.1117/12.763285)), *XiangNing Kang* ([/profile/Xiang-Ning.Kang-53593](https://doi.org/10.1117/12.763285)), *Tao Dai*, *Chang Xiong*, *GuoYi Zhang*, *Yong Chen* ([/profile/Yong.Chen-54729](https://doi.org/10.1117/12.763285))

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NOVEL LED STRUCTURE II

Hybrid colloidal nanocrystal-organics based LEDs

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Aurora Rizzo ([/profile/Aurora.Rizzo-68185](https://doi.org/10.1117/12.773799)), *Yanqin Li* ([/profile/Yanqin.Li-60237](https://doi.org/10.1117/12.773799)), *Marco Mazzeo*, *Giuseppe Gigli* ([/profile/Giuseppe.Gigli-28934](https://doi.org/10.1117/12.773799))

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GaN-based light emitting diodes with large area surface nano-structures patterned by anodic aluminum oxide

templates ([/conference-proceedings-of-spie/6910/69100P/GaN-based-light-emitting-diodes-with-large-area-surface-](#)

[nano/10.1117/12.763416.full](#))  Paper

[Tao Dai](#), [Bei Zhang](#) ([/profile/Bei.Zhang-65239](#)), [Xiangning Kang](#) ([/profile/Xiang-Ning.Kang-53593](#)), [Kui Bao](#) ([/profile/Kui.Bao-90365](#)), [Wenzhu Zhao](#), [Dongshen Xu](#) ([/profile/Dongsheng.Xu-56887](#)), [Zizhao Gan](#)

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Submicron-thick microcavity InGaN light emitting diodes ([/conference-proceedings-of-spie/6910/69100R/Submicron-thick-](#)

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[Yong-Seok Choi](#) ([/profile/Yong-Seok.Choi-57350](#)), [Michael Iza](#), [Elison Matioli](#), [Gregor Koblmüller](#) ([/profile/Gregor.Koblmuller-163894](#)), [James S. Speck](#) ([/profile/James.Speck-114580](#)), [Claude Weisbuch](#) ([/profile/Claude.Weisbuch-7938](#)), [Evelyn L. Hu](#)

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LED APPLICATION

Surgical retractor with RGB-WHITE LEDs ([/conference-proceedings-of-spie/6910/69100T/Surgical-retractor-with-RGB-WHITE-](#)

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[Jun-ichi Shimada M.D.](#) ([/profile/Jun-ichi.Shimada-69889](#)), [Daishiro Kato](#), [Kunihiko Terauchi](#) ([/profile/Kunihiko.Terauchi-88484](#)), [Kazuhiro Itoh](#), [Masashi Yanada](#), [Masanori Shimomura](#), [Hiroaki Tsuneduka](#), [Yoichi Kawakami](#) ([/profile/Yoichi.Kawakami-15791](#))

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Smart LED light source driver for machine vision system ([/conference-proceedings-of-spie/6910/69100U/Smart-LED-light-source-](#)

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High-power LED illumination system for photosynthetic research on potted plant canopies ([/conference-proceedings-of-spie/6910/69100V/High-power-LED-illumination-system-for-photosynthetic-research-on-potted/10.1117/12.762636.full](#)) Paper[Birgitte Thestrup](#) ([/profile/Birgitte.Thestrup-22996](#)), [Carsten Dam-Hansen](#), [Janni Bjerregaard Lund](#), [Eva Rosenqvist](#)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 69100V (2008) <https://doi.org/10.1117/12.762636> (<https://doi.org/10.1117/12.762636>)[Read Abstract +](#)**ePaper** ([/conference-proceedings-of-spie/6910/69100W/ePaper/10.1117/12.763222.full](#)) Paper[Dhananjay V. Gadre](#), [Vasudev Lal](#), [Sulochana Dhar](#) ([/profile/Sulochana.Dhar-84863](#)), [Anshul Kumar](#)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 69100W (2008) <https://doi.org/10.1117/12.763222> (<https://doi.org/10.1117/12.763222>)[Read Abstract +](#)**(AlGaIn)N UV LEDs for integrated metal-oxide based ozone sensors** ([/conference-proceedings-of-spie/6910/69100X/AlGaInN-UV-LEDs-for-integrated-metal-oxide-based-ozone-sensors/10.1117/12.761128.full](#)) Paper[J. Wagner](#) ([/profile/Hans-Joachim.Wagner-6115](#)), [Ch. Y. Wang](#), [C.-C. Röhlig](#), [M. Maier](#) ([/profile/Markus.Maier-94576](#)), [M. Kunzer](#), [T. Passow](#), [W. Schirmacher](#), [W. Pletschen](#), [V. Cimalla](#), *et al.*Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 69100X (2008) <https://doi.org/10.1117/12.761128> (<https://doi.org/10.1117/12.761128>)[Read Abstract +](#)**ZNO AND PHOSPHORS****Phosphors for solid state lighting** ([/conference-proceedings-of-spie/6910/691010/Phosphors-for-solid-state-lighting/10.1117/12.760066.full](#)) Paper[M. Zachau](#) ([/profile/Martin.Zachau-88442](#)), [D. Becker](#), [D. Berben](#), [T. Fiedler](#), [F. Jermann](#), [F. Zwaschka](#)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 691010 (2008) <https://doi.org/10.1117/12.760066> (<https://doi.org/10.1117/12.760066>)[Read Abstract +](#)**Decay mechanisms of lumen and chromaticity for high-power phosphor-based white-light-emitting diodes in****thermal aging** ([/conference-proceedings-of-spie/6910/691011/Decay-mechanisms-of-lumen-and-chromaticity-for-high-power-phosphor/10.1117/12.760906.full](#)) Paper

Chun-Chin Tsai (</profile/Chun-Chin.Tsai-88580>), *Ming-Hung Chen*, *Chao-Wei Lee*, *Yuan-Tsun Lo*, *Yi-Cheng Hsu* (</profile/Yi-Cheng.Hsu-64684>), *Wood-Hi Cheng* (</profile/Wood-Hi.Cheng-130991>).

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LED PROPERTIES

Radiative efficiency and spontaneous recombination rate of staggered InGaN quantum well LED at 420-510 nm

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Ronald A. Arif (</profile/Ronald.Arif-60202>), *Hongping Zhao* (</profile/Hongping.Zhao-88971>), *Yik-Khoon Ee* (</profile/Yik-Khoon.Ee-70710>), *Nelson Tansu*

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Investigation of process parameters towards high efficiency silicon light-emitting diodes (</conference-proceedings-of-spie/6910/691015/Investigation-of-process-parameters-towards-high-efficiency-silicon-light-emitting/10.1117/12.763787.full>) Paper

Grant Z. Pan (</profile/Grant.Pan-90369>), *Dae H. Pak* (</profile/Dae-Hoon.Pak-88855>), *Jaime Peretzman*, *Li P. Ren*

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LED PACKAGING

High performance encapsulants for ultra high-brightness LEDs (</conference-proceedings-of-spie/6910/691017/High-performance-encapsulants-for-ultra-high-brightness-LEDs/10.1117/12.761724.full>) Paper

David W. Mosley (</profile/David.Mosley-79128>), *Kathy Auld*, *David Conner*, *Jay Gregory*, *Xian-Qian Liu*, *Angelo Pedicini*, *David Thorsen*, *Morris Wills*, *Garo Khanarian* (</profile/Garo.Khanarian-5232>), *et al.*

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Advances in LED packaging and thermal management materials ([/conference-proceedings-of-spie/6910/691018/Advances-in-](/conference-proceedings-of-spie/6910/691018/Advances-in-LED-packaging-and-thermal-management-materials/10.1117/12.761839.full)[LED-packaging-and-thermal-management-materials/10.1117/12.761839.full](/conference-proceedings-of-spie/6910/691018/Advances-in-LED-packaging-and-thermal-management-materials/10.1117/12.761839.full))  Paper[Carl Zweber \(/profile/Carl.Zweber-16403\)](/profile/Carl.Zweber-16403)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 691018 (2008) <https://doi.org/10.1117/12.761839>
(<https://doi.org/10.1117/12.761839>)[Read Abstract +](#)**Novel chip coating approaches to improve white LED technology** ([/conference-proceedings-of-spie/6910/69101A/Novel-chip-](/conference-proceedings-of-spie/6910/69101A/Novel-chip-coating-approaches-to-improve-white-LED-technology/10.1117/12.764477.full)[coating-approaches-to-improve-white-LED-technology/10.1117/12.764477.full](/conference-proceedings-of-spie/6910/69101A/Novel-chip-coating-approaches-to-improve-white-LED-technology/10.1117/12.764477.full))  Paper[Paul Hartmann \(/profile/Paul.Hartmann-74959\)](/profile/Paul.Hartmann-74959), [Marko Schweighart](/profile/Marko.Schweighart), [Christian Sommer \(/profile/Christian.Sommer-4864\)](/profile/Christian.Sommer-4864), [Franz-P. Wenzl \(/profile/Franz-Peter.Wenzl-25939\)](/profile/Franz-Peter.Wenzl-25939), [Ernst Zinterl](/profile/Ernst.Zinterl), [Hans Hoschopf \(/profile/Hans.Hoschopf-81513\)](/profile/Hans.Hoschopf-81513), [Peter Pachler](/profile/Peter.Pachler), [Stefan Tasch](/profile/Stefan.Tasch)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 69101A (2008) <https://doi.org/10.1117/12.764477>
(<https://doi.org/10.1117/12.764477>)[Read Abstract +](#)**POSTER SESSION****Stability of electroluminescent conjugated with fluoro groups in vinylene units** ([/conference-proceedings-of-](/conference-proceedings-of-spie/6910/69101F/Stability-of-electroluminescent-conjugated-with-fluoro-groups-in-vinylene-units/10.1117/12.762221.full)[spie/6910/69101F/Stability-of-electroluminescent-conjugated-with-fluoro-groups-in-vinylene-units/10.1117/12.762221.full](/conference-proceedings-of-spie/6910/69101F/Stability-of-electroluminescent-conjugated-with-fluoro-groups-in-vinylene-units/10.1117/12.762221.full))  Paper[Jaeyeon Jung \(/profile/Jaeyeon.Jung-88810\)](/profile/Jaeyeon.Jung-88810), [Younggeup Jin](/profile/Younggeup.Jin), [Jinwoo Kim \(/profile/Jinwoo.Kim-76419\)](/profile/Jinwoo.Kim-76419), [Suhee Song \(/profile/Suhee.Song-83519\)](/profile/Suhee.Song-83519), [Jaehong Kim](/profile/Jaehong.Kim), [Sun Hee Kim \(/profile/Sun-Hee.Kim-57020\)](/profile/Sun-Hee.Kim-57020), [Youna Choi](/profile/Youna.Choi), [Kwanghee Lee \(/profile/Kwanghee.Lee-19380\)](/profile/Kwanghee.Lee-19380), [Hongsuk Suh \(/profile/Hongsuk.Suh-45211\)](/profile/Hongsuk.Suh-45211)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 69101F (2008) <https://doi.org/10.1117/12.762221>
(<https://doi.org/10.1117/12.762221>)[Read Abstract +](#)**The color tuning of PPV derivative by substituted tetrakis-ethylhexyloxy groups** ([/conference-proceedings-of-](/conference-proceedings-of-spie/6910/69101G/The-color-tuning-of-PPV-derivative-by-substituted-tetrakis-ethylhexyloxy/10.1117/12.762230.full)[spie/6910/69101G/The-color-tuning-of-PPV-derivative-by-substituted-tetrakis-ethylhexyloxy/10.1117/12.762230.full](/conference-proceedings-of-spie/6910/69101G/The-color-tuning-of-PPV-derivative-by-substituted-tetrakis-ethylhexyloxy/10.1117/12.762230.full))  Paper[Younggran Goo \(/profile/Younggran.Goo-88811\)](/profile/Younggran.Goo-88811), [Younggeup Jin](/profile/Younggeup.Jin), [Suhee Song \(/profile/Suhee.Song-83519\)](/profile/Suhee.Song-83519), [Jin Young Kim \(/profile/Jin-Young.Kim-69330\)](/profile/Jin-Young.Kim-69330), [Kwanghee Lee \(/profile/Kwanghee.Lee-19380\)](/profile/Kwanghee.Lee-19380), [Hongsuk Suh \(/profile/Hongsuk.Suh-45211\)](/profile/Hongsuk.Suh-45211)Proceedings Volume Light-Emitting Diodes: Research, Manufacturing, and Applications XII, 69101G (2008) <https://doi.org/10.1117/12.762230>
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