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Analysis and Optimization of Volume Diffusors

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In contrast to imaging optics diffusors are typically used to achieve homogeneous luminance distribution for display and lighting applications. However, a detailed quantitative understanding and numerical description of their optical performance are very unconfident. In this contribution we focus on volume diffusors and present results on three types of particle-matrix-material combinations.

1 Introduction

LEDs are today's mega trend in automotive, street and general lighting [1]. For these applications the specified far-field radiant intensity often has to be achieved by specific collimation optics. Fig. 1 displays a typical setup of a beam shaping optic, sometimes called TIR-lens [3].

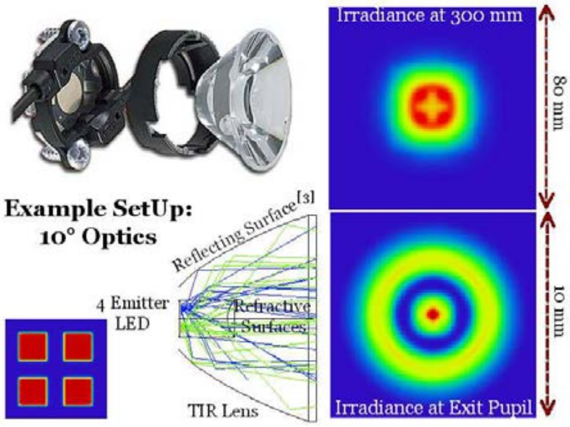

Fig. 1 *Typical setup of a beam shaping optics [3] and simulation results for a white multi-die LED with four emitters in combination with a collimation TIR lens.*

Today's high performance white LEDs often use an array of blue emitters (called multi-die) behind the fluorescence layer. In Fig. 1 simulation results are shown for a multi-die LED containing four emitters in combination with a TIR lens. The radiant intensity distribution and the luminance profile clearly show the "footprint" of the four emitter configuration. In order to overcome these inhomogeneities optical diffusors are used. We focus on volume diffusors and present results on three types of particle-matrix-material combinations.

2 Light Scattering Basics

The scatter particle concentration of volume diffusors is defined by the package fraction η and limiting package fraction η_{Limit} for single particle scattering:

$$\eta_{Limit} = \frac{4}{3}\frac{R_{Scat}}{D_{Pr}} \approx \frac{R_{Scat}}{D_{Pr}} \qquad (1)$$

(R_{Scat}: Particle radius, D_{Pr}: Sample thickness)

Within this limit the scattering behaviour of any specific volume diffusor can experimentally be determined by a goniometer setup as shown in Fig. 2.

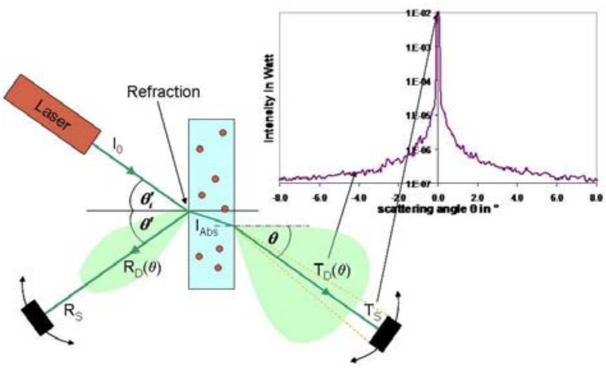

Fig. 2 *Schematically view of a goniometer setup and typical intensity profile for a volume diffusor.*

Using a turnable detector the angular distribution of the radiant intensity in reflection and transmission can be recorded. The diagram in Fig.2 shows a typical result for a volume diffusor. From this intensity profile the so-called particle form factor

$$P(Q) = \frac{I^{Scat}(Q)}{I_0^{Scat}(Q)} \qquad (2)$$

can be determined, where Q is the norm of the light scattering vector

$$Q = \left(\frac{4\pi n_{Matrix}}{\lambda_0}\right) \cdot \sin\left(\frac{\theta}{2}\right) \qquad (3)$$

For single particle scattering the angular radiant intensity can be described by the Mie-theory [4]. For spherical particles of index n_{Scat} and radius

R_{Scat} within the matrix material of index n_{Matrix} the particle form factor

$$P(Q) = \exp\left(-\frac{Q^2 R_{Scat}^2}{5}\right) \qquad (4)$$

is valid for $Q^* R_{Scat} \ll 1$. Fig. 3 displays the principle numerical behaviour within this theoretical framework.

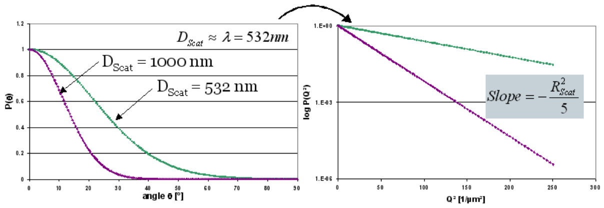

Fig. 3 *Principle numerical behaviour of single particle Mie-scattering. Left: P(θ); right: Linear behaviour for log (P(Q²)).*

3 Results for a model volume diffusor

In order to validate our optical setup we applied this procedure at a water based model scattering liquid (n_{Matrix} = 1.33), containing a soluble concentration of latex-polystyrene spheres ($n_{Scatter}$ = 1.59) of radius $R_{Scat} \approx 150$ nm [5]. We prepared 4 package fractions and experimentally determined the scattering behaviour in transmission using the goniometer setup of Fig.2. Fig.4 displays the results P(Q²) and the linear fit to (4).

The measured straylight distributions and the theoretical linear predictions show excellent agreement. The inset of Fig.4 shows that the R_{Scat} values extracted from the linear fits to (4) decrease with increasing package fraction. This seems to be unexpected, because the particle radius should be independent from the package fraction. However, one has to consider that the 4 used package fraction are close to η_{Limit}. With increasing η the amount of multiple scattered light increases which flattens the P(Q²) behaviour. This leads to apparently smaller R_{Scat} values.

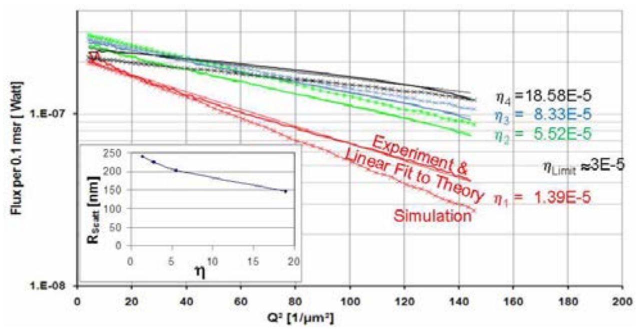

Fig. 4 *Experimental results, a fit to Mie-theory and simulation results at the 4 package fractions $\eta_1 \ldots \eta_4$ of scattering liquid.*

Additionally we modeled the goniometer setup in combination with the different diffusor parameters in the optical design software tool Zemax [6] and received very similar simulation results (crossed curves in Fig.4).

Driven by this sufficient numerical agreement between the goniometer experiment and the corresponding simulation we modeled the TIR lens of Fig. 1 in Zemax using a model volume diffusor as bulk material. Fig.5 compares the simulation results from Fig. 1 with the data for the model volume diffusor as TIR lens material.

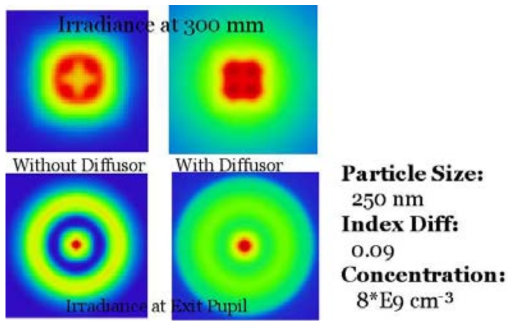

Fig. 5 *Comparison of the simulation results from Fig. 1 with the volume diffusor as bulk material.*

The radiant intensity distribution as well as the luminance profile shows significantly improved smoothness leading to much more homogeneous illumination behaviour.

4 Choice of realistic volume diffusors

However, we propose two alternative material systems to be used for realistic TIR lenses. The Evonik Röhm GmbH offers several types of diffusor materials, based on the matrix material Plexiglas© [7]. As Mie scattering particles organic or inorganic phases of different size, shape, index and package fraction can be individually chosen depending on the specific application. The second material system might be based on inorganic glass ceramics. However during the material synthesis a special thermal treatment produces a well defined concentration of different crystalline particles within the glassy matrix. These phases might also act as light scattering centers.

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