BTDF – Benefit and use for the characterization of volume diffusors

Workshop on BTDF measurement

2022-04-26, Madrid

Dr. Rafael Oser

Covestro – leading in the world of plastics

Strong

- €15.9 bn in sales
- ~17,900 employees[1]

Useful

- Plastics, pre-products and solutions
- For many industries

Global

- 50 production sites globally
- Close to customers and partners

Innovative

- ~1,500 employees in research and development
- 80 years of ideas and inventions

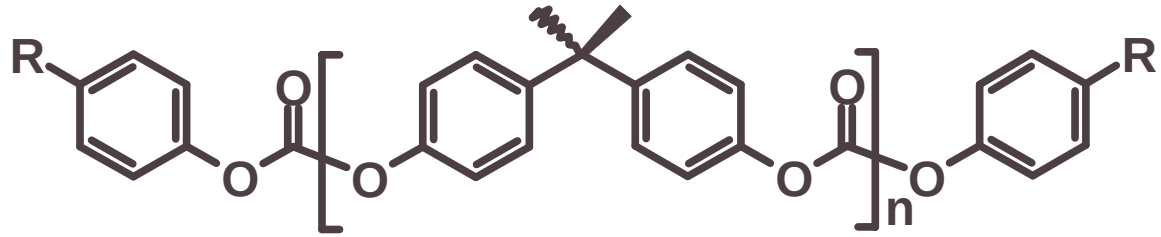
Information is based on financial results for 2021, except amount of employees and amount of global production sites. Those are as of June 30, 2021.
[1]calculated as full-time equivalent (FTE)

Introduction Polycarbonate

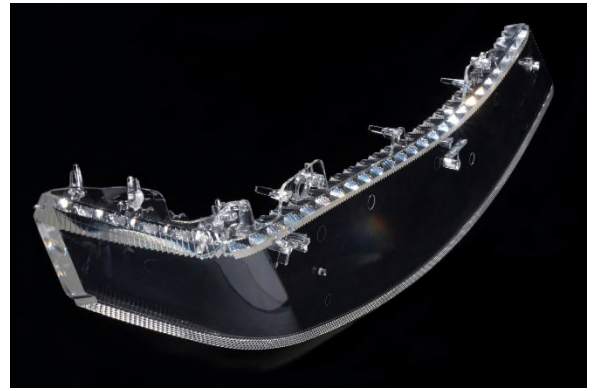
Key Properties of Polycarbonate – Overview

Trade Name: Makrolon®

- High Transmission
- Toughness

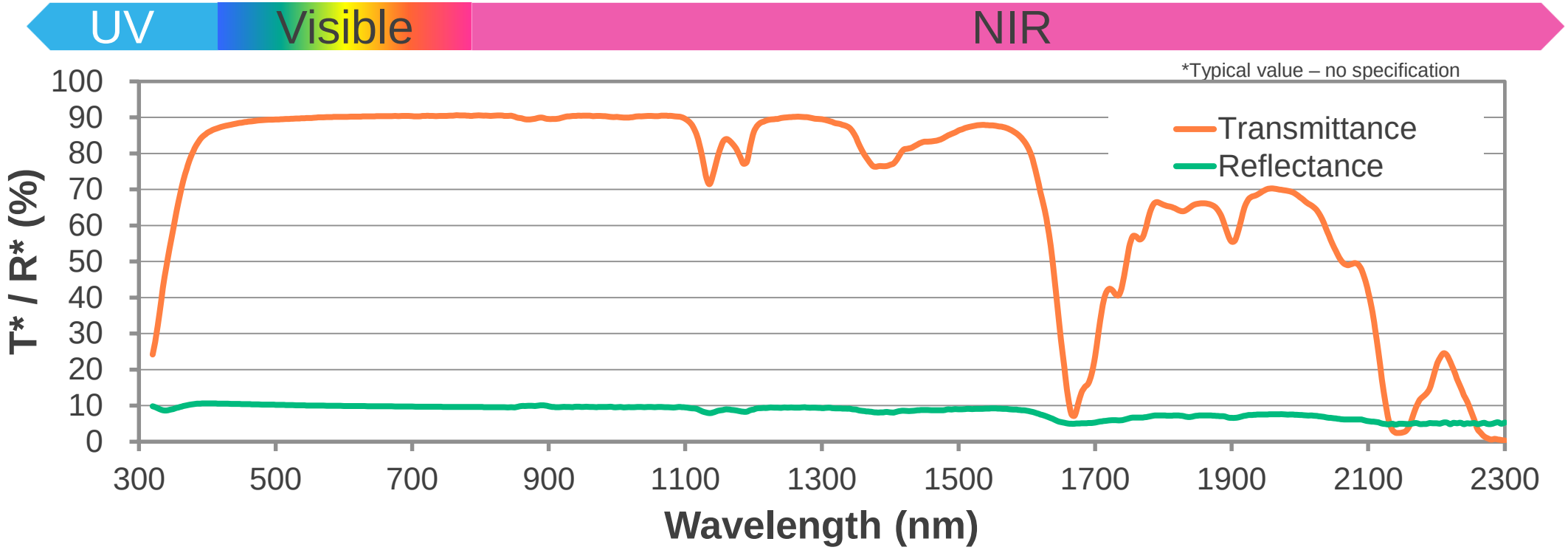


- Flame Retardancy
- Heat Resistance



Introduction Polycarbonate

T-/R-Spectrum of PC: Makrolon® 2808 (3.2mm)



UV-Range:	**UV-Absorber**	→	Material protection, UV-Cut (Lens)
Visible-Range:	**Color**	→	Coloring, Tint (Fbl)
NIR-Range:	**IR-Absorber**	→	Safety Glasses (Welding, Laser), Solar Radiation

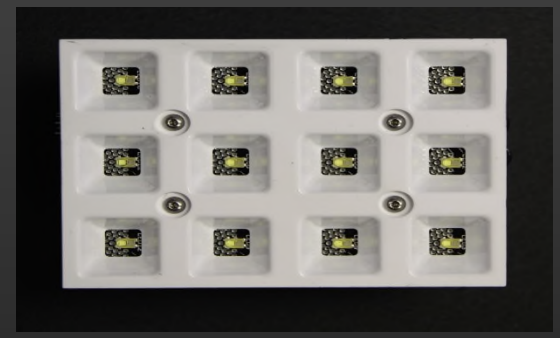
Introduction Polycarbonate

Selection of Optical Product Lines of Makrolon ®

Mobility:

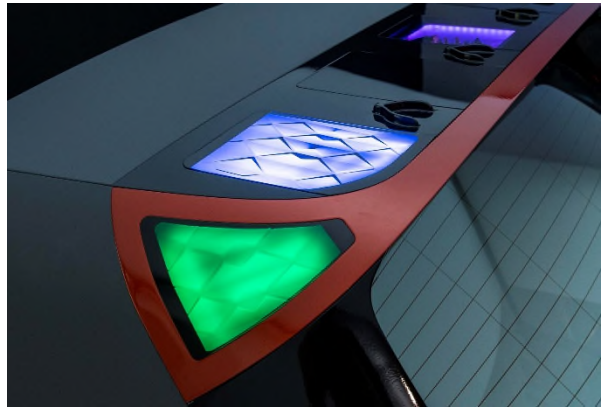
Makrolon ® AX & AG	Makrolon ® Ai	Makrolon ® AL & LED
Exterior	Interior	Headlamp
		

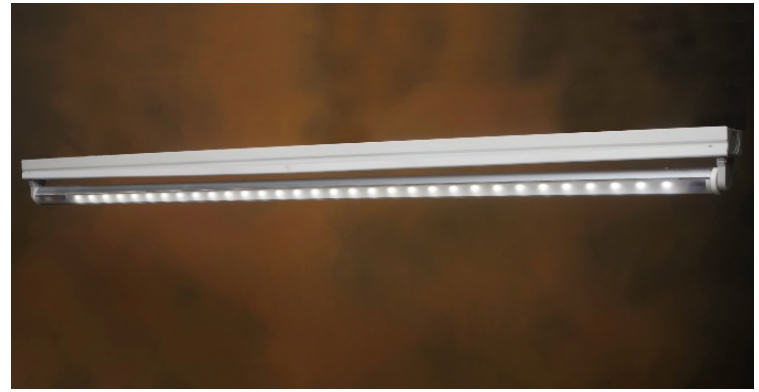
General Lighting:

Makrolon ® LED5xxx	Makrolon ® DQ	Makrolon ® RW
Lens	Diffusor	Reflector
		

Introduction Polycarbonate

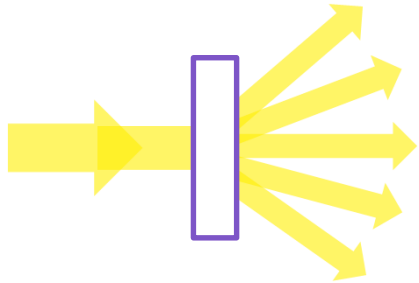
Applications for volume diffusors for LED lighting





Volume Diffusors

How to avoid the bright spot of a LED?



Distribution of light over a wide angular range

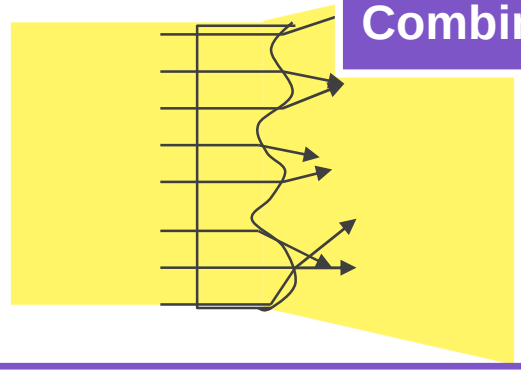
Refraction

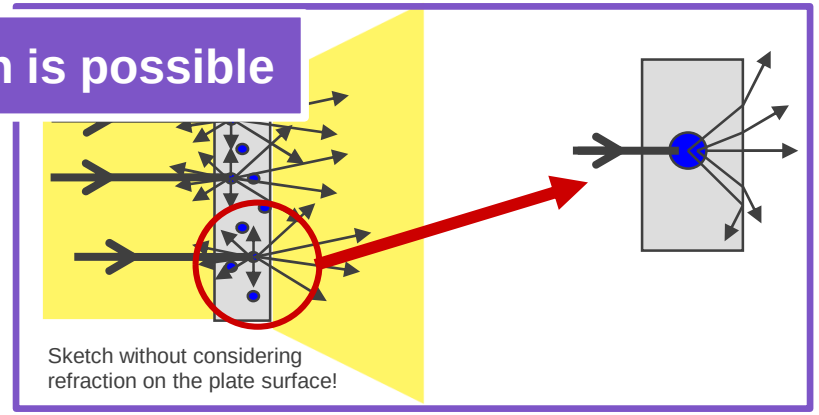
→ Surface structure (frosted glass, pyramids)

Scattering

→ Bulk diffuser, scattering by objects within the bulk

Combination of both is possible

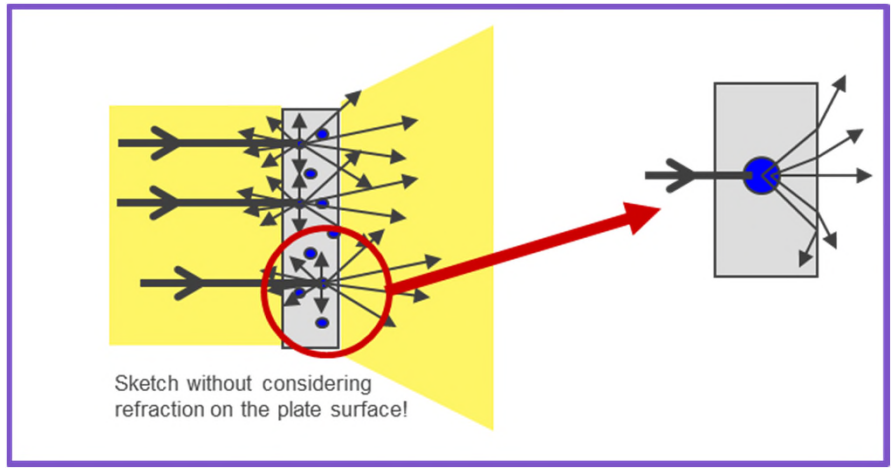




Sketch without considering refraction on the plate surface!

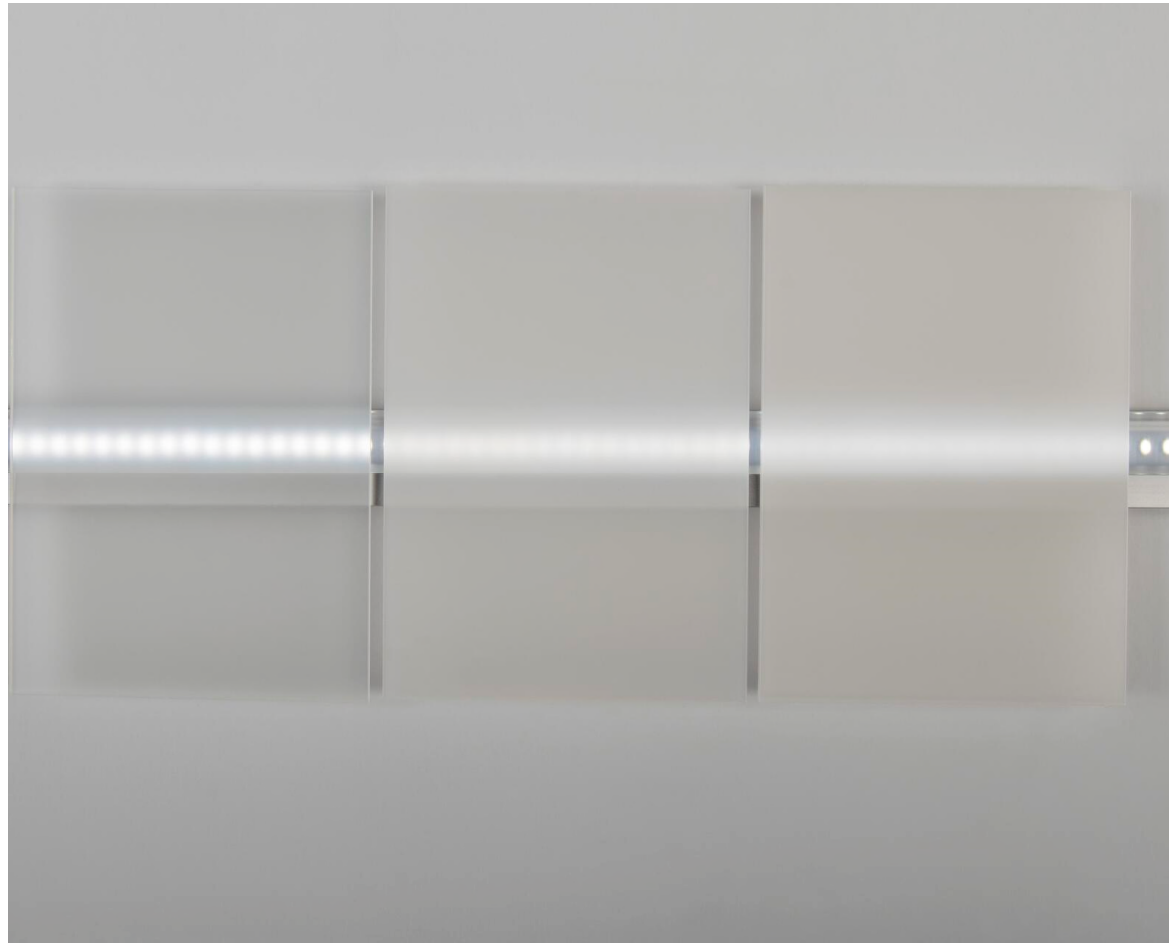
Volume Diffusors

Optimizing the scattering power



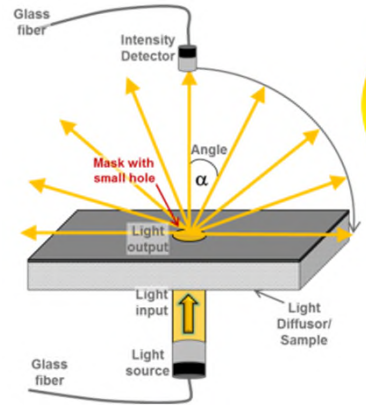
Scattering power adjusted by:

- **Scattering agents:**
  - RI, Size, Structure
- **Concentration of scattering agent**
- **Thickness**



Volume Diffusors

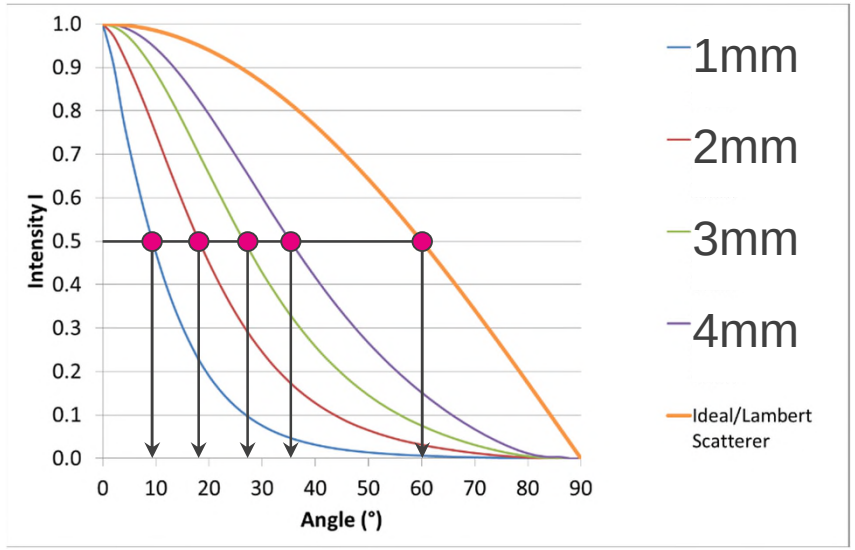
Characterization of scattering power via HPA



Measurement of the HPA = Half Power Angle

- HPA is used to describe the scattering power on data sheet level.
- Measurement method is not standardized so far

Max. HPA = 60° (Ideal Scatter)



	1mm	2mm	3mm	4mm
HPA* =	9.4°	18.1°	26.6°	35.3°

* Typical value – no specification

Volume Diffusors

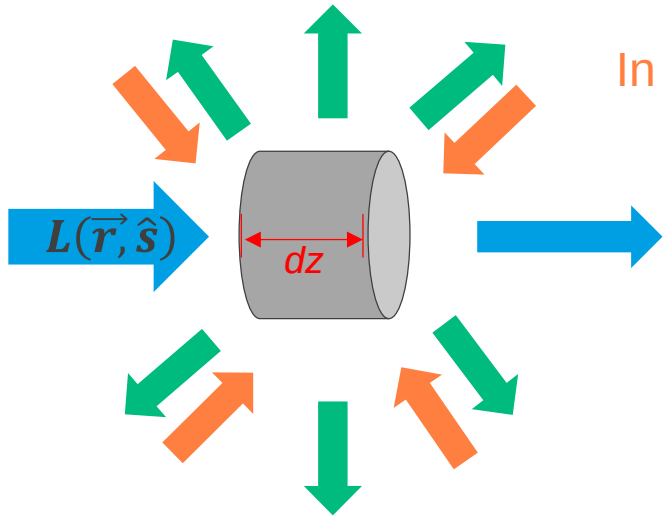
Generating optical material data for simulation

Radiative Transfer Equation for volume diffusors:

The **RTE** describes the redistribution of the radiance in a differential volume element due to absorption and scattering:

$$(\hat{s}\cdot\nabla)L(\vec{r},\hat{s}) = -(\mu_a+\mu_s)L(\vec{r},\hat{s}) + \mu_s\int_{4\pi}L(\vec{r},\hat{s}')p(\hat{s}'\cdot\hat{s})d\Omega'$$

In scattering



Material Parameter:

μ_a**:** Absorption Coefficient (1/mm) → Absorption

μ_s**:** Scattering Coefficient (1/mm) → Out scattering

$p(\hat{s}'\cdot\hat{s})$**:** Phase function → Single particle scatter

We rely on commercial products.

Remark:
Clear transparent material:
μ_s= 0, p=0 → RTE leads to Lambert-Beer's Law

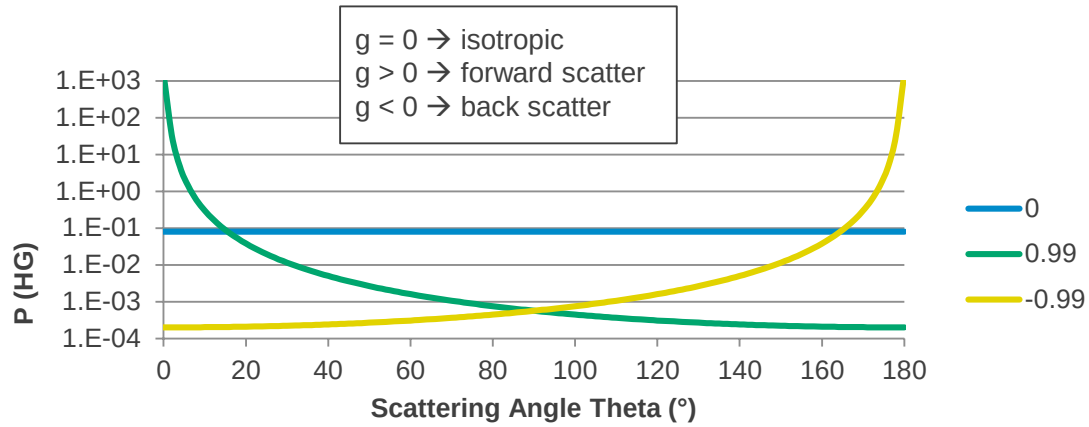
Determination the material parameter for volume diffusors

Model for phase functions

Henyey-Greenstein (HG 1941):

$$p_{HG}(\theta, g) = \frac{1}{4\pi} \frac{1 - g^2}{(1 + g^2 - 2g\ \cos\theta)^{\frac{3}{2}}}$$

g : Anisotropy factor (-1 < g < 1)



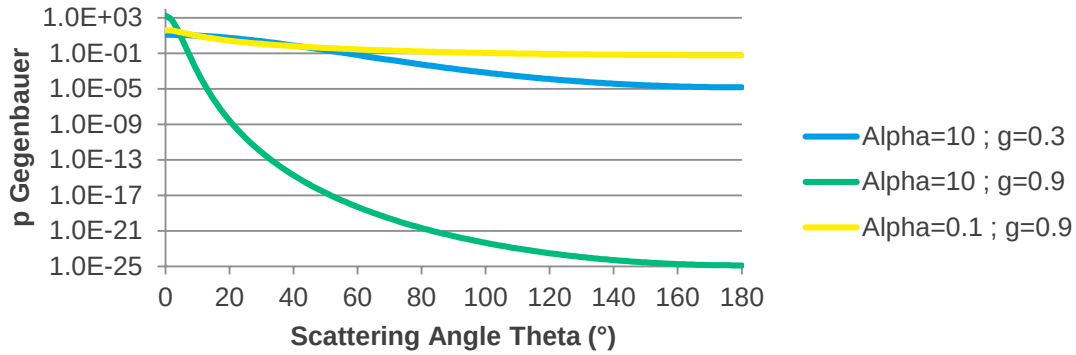
Gegenbauer (Reynolds-McCormick 1980):

$$p_{Geg}(\theta, g_{Geg}, \alpha) = \frac{\alpha g_{Geg}(1 - g_{Geg}^2)^{2\alpha}}{\pi\left[(1 + g_{Geg})^{2\alpha} - (1 - g_{Geg})^{2\alpha}\right](1 + g_{Geg}^2 - 2g_{Geg}\cos\theta)^{(1+\alpha)}}$$

g_{Geg} : Anisotropy factor

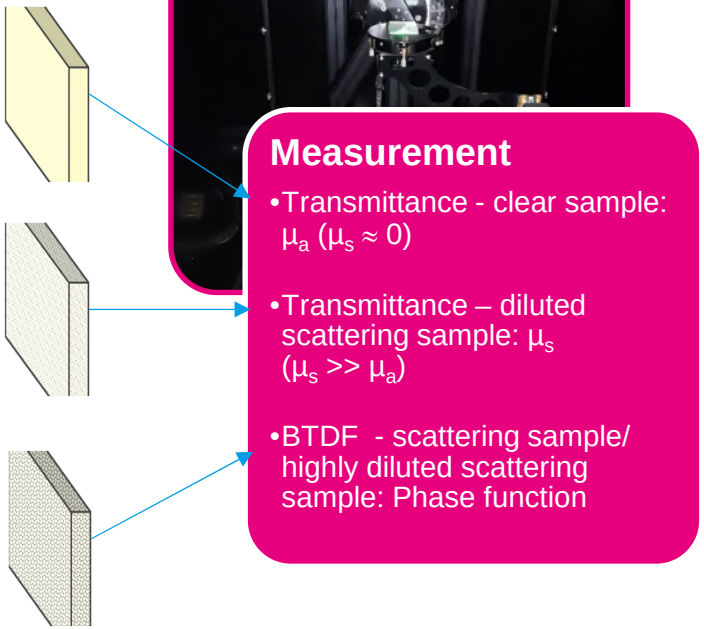
$-1 < g_{Geg} < 1$ and $\alpha > -½$

($\alpha = ½ \rightarrow p_{Geg} = p_{HG}$)



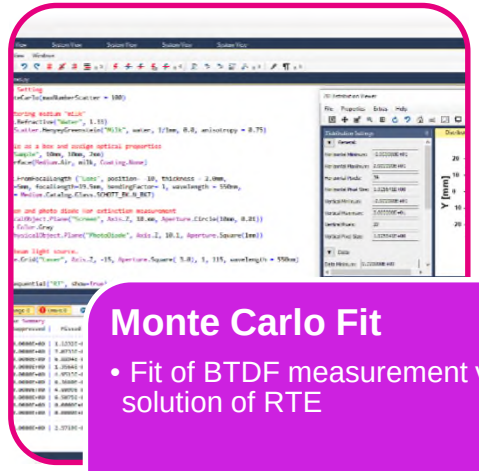
Determination the material parameter for volume diffusors

Approach according to VDI/VDE 5596-3*



Measurement

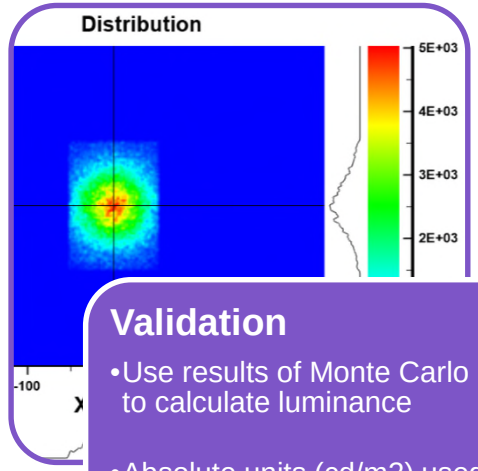
- Transmittance - clear sample: μ_a ($\mu_s \approx 0$)
- Transmittance – diluted scattering sample: μ_s ($\mu_s >> \mu_a$)
- BTDF - scattering sample/ highly diluted scattering sample: Phase function



Monte Carlo Fit

- Fit of BTDF measurement via solution of RTE
- Starting parameter from measurements

→ **Result:** μ_a, μ_s, phase function parameters



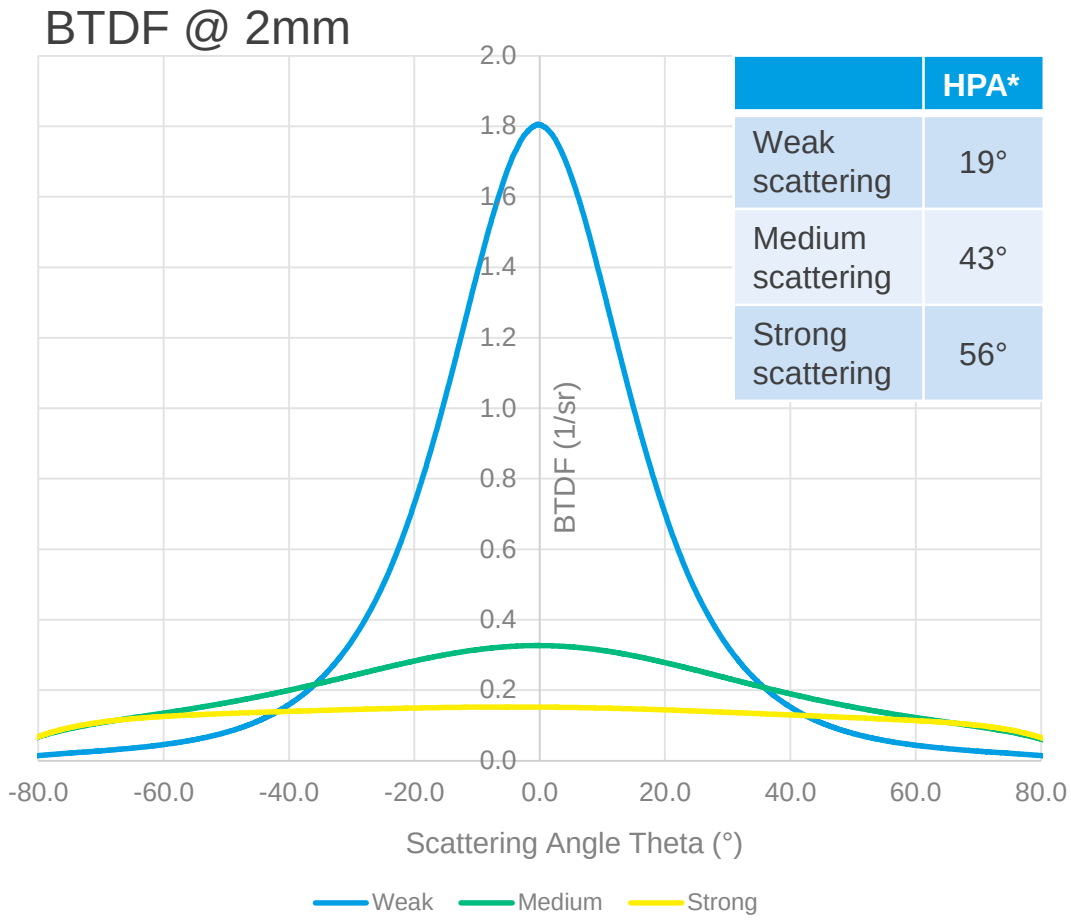
Validation

- Use results of Monte Carlo Fit to calculate luminance
- Absolute units (cd/m2) used

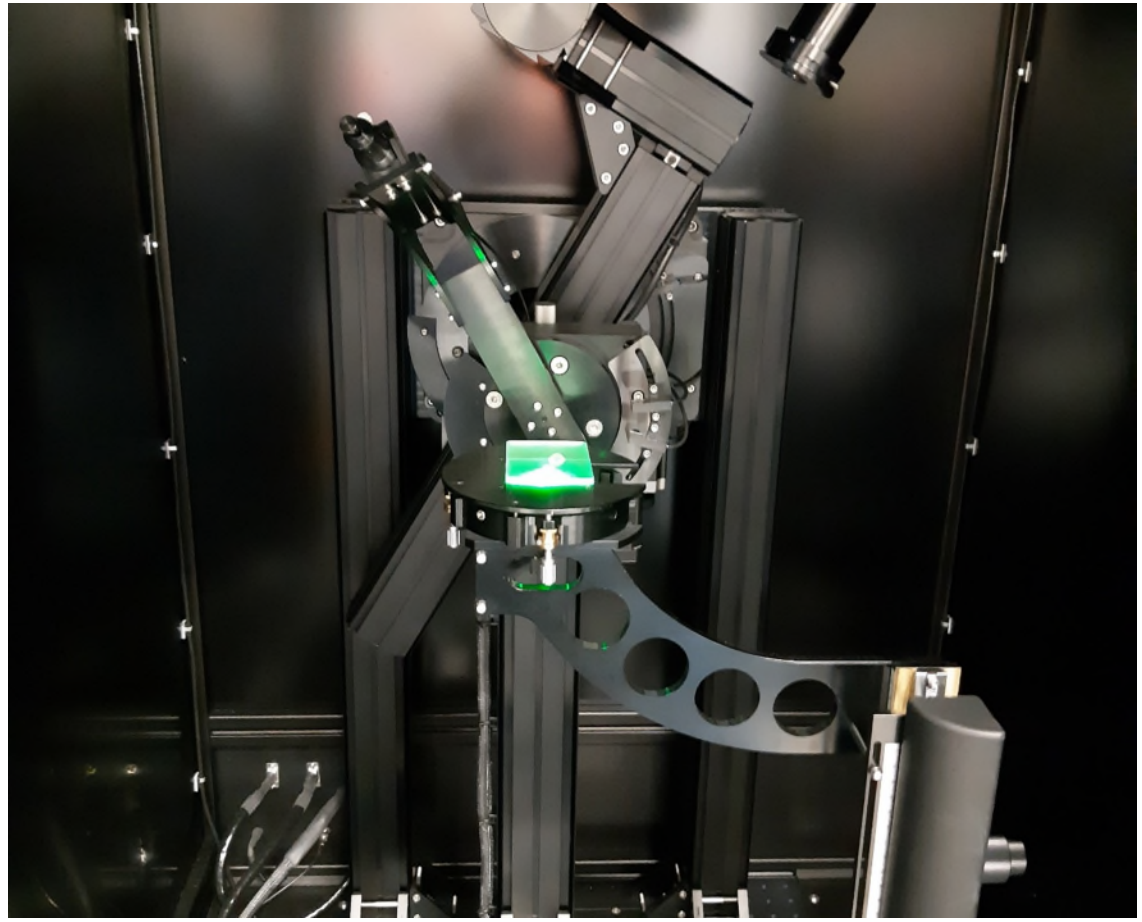
*www.vdi.de/5596

Determination the material parameter for volume diffusors

BTDF Measurement



	HPA*
Weak scattering	19°
Medium scattering	43°
Strong scattering	56°



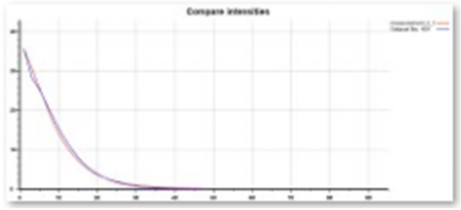
*HPA: Half Power Angle

Determination the material parameter for volume diffusors

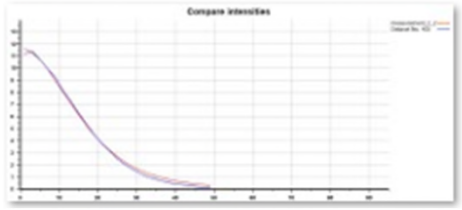
Fit Results via Monte Carlo ray tracing (Gegenbauer-Model)

Weak scattering sample

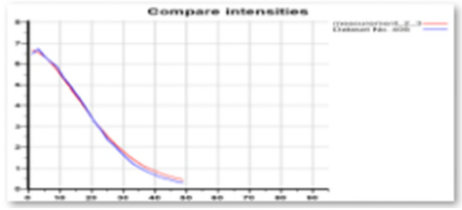
1 mm



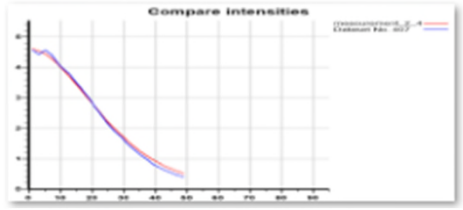
2 mm



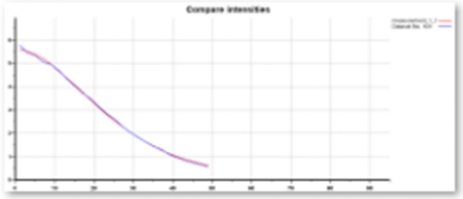
3 mm

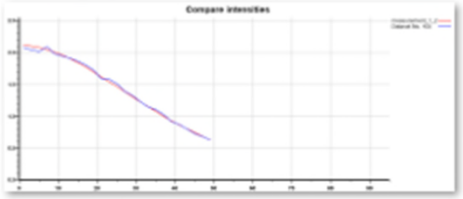


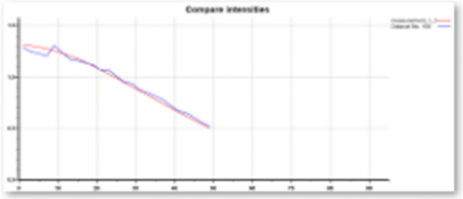
4 mm

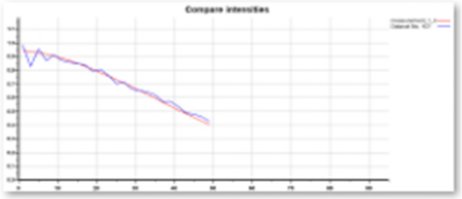


Medium scattering sample

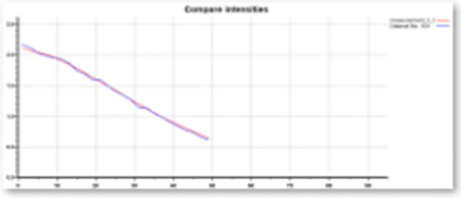


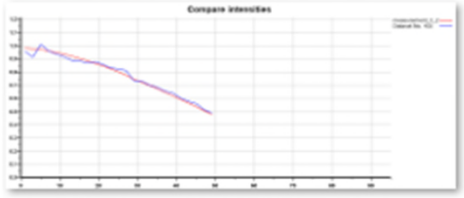


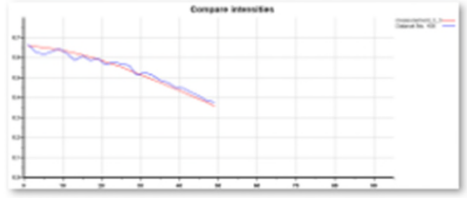


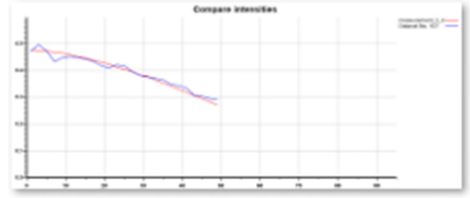


Strong scattering sample





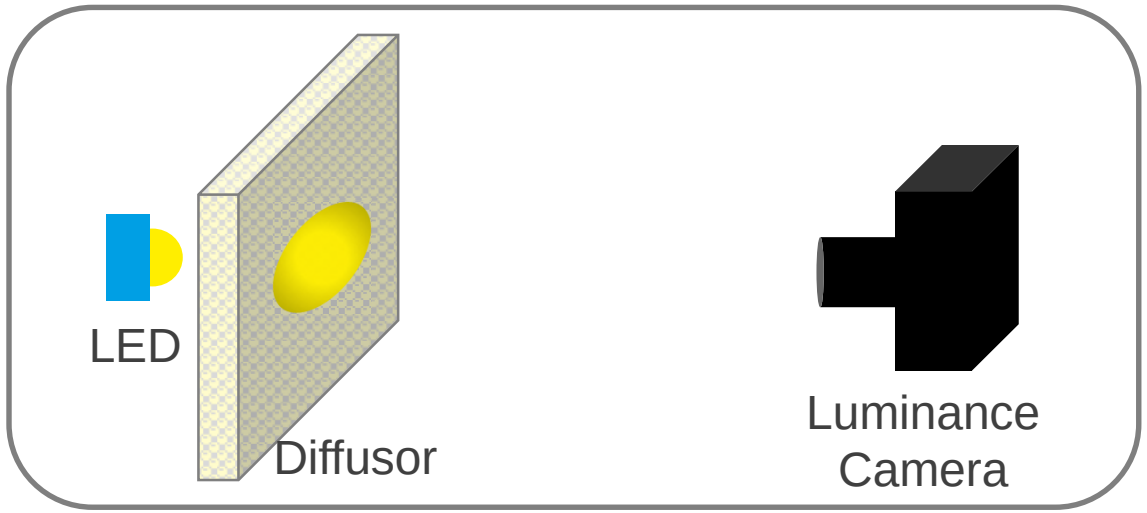


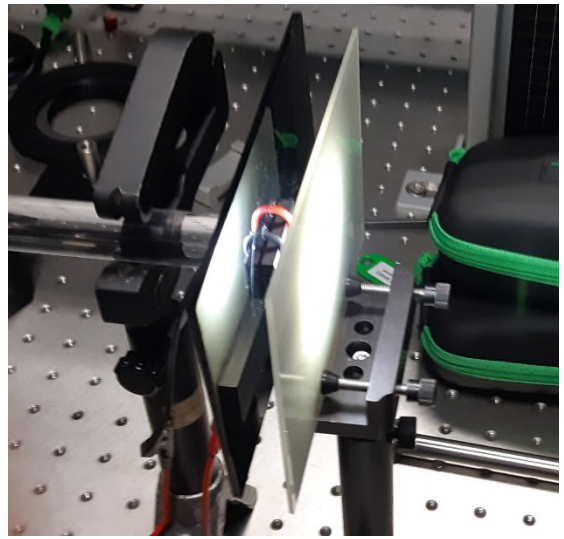


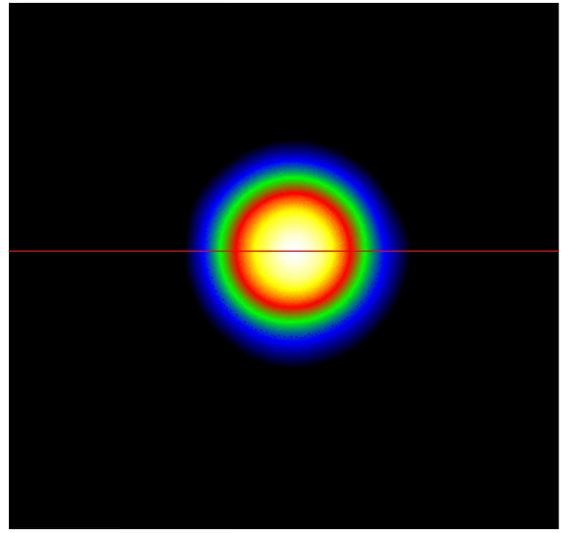
Determination the material parameter for volume diffusors

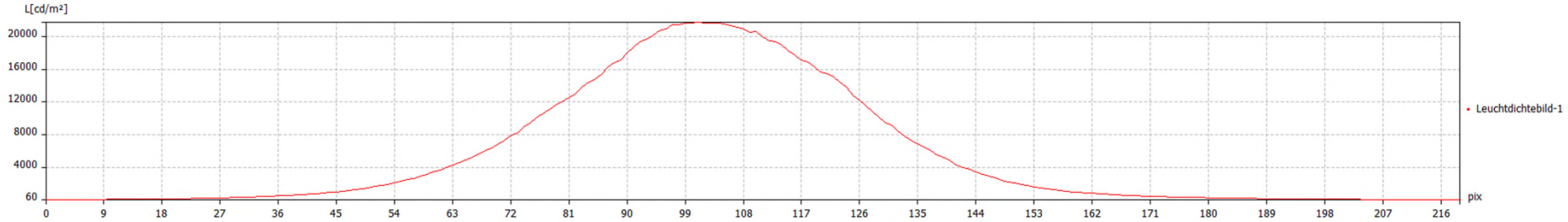
Validation of the results of the fitting process

Validation via Luminance measurement:







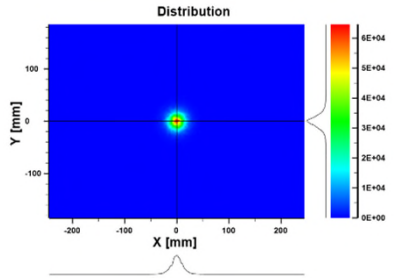


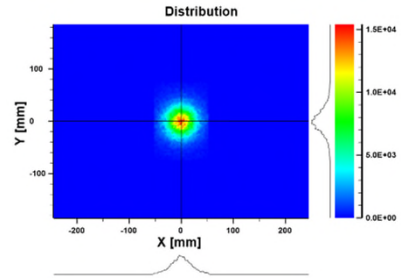
Results

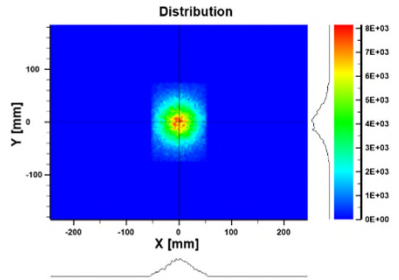
Comparison to luminance – LED CCT: 4000K

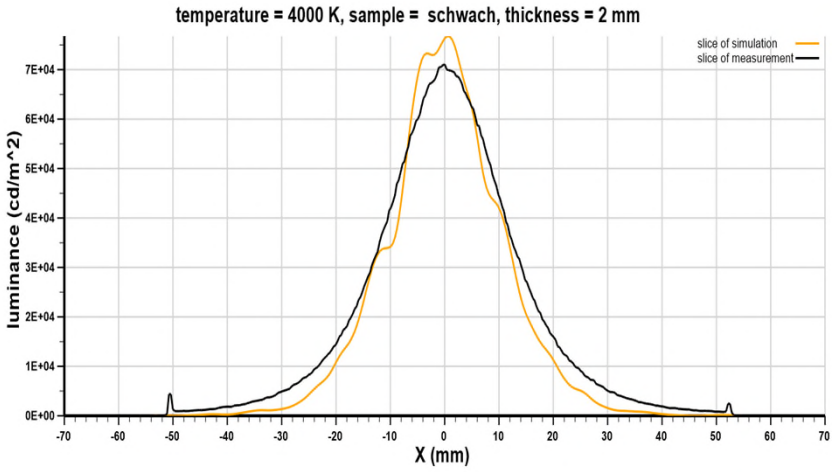
Sample thickness 2mm

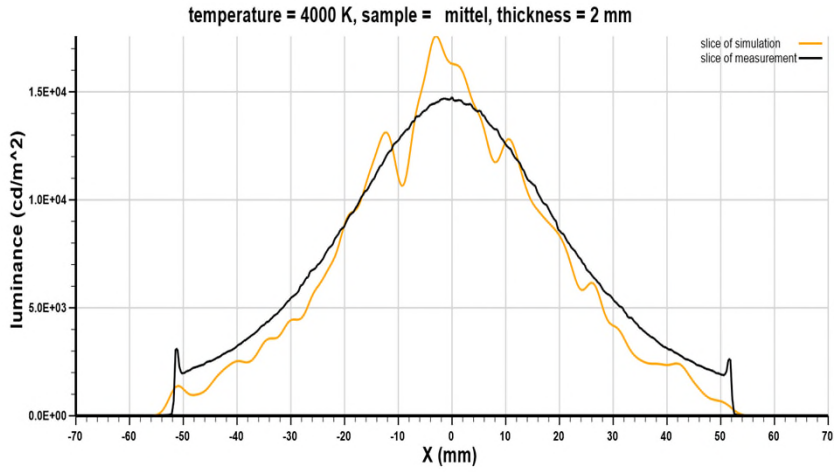
Weak scattering sample	Medium scattering sample	Strong scattering sample

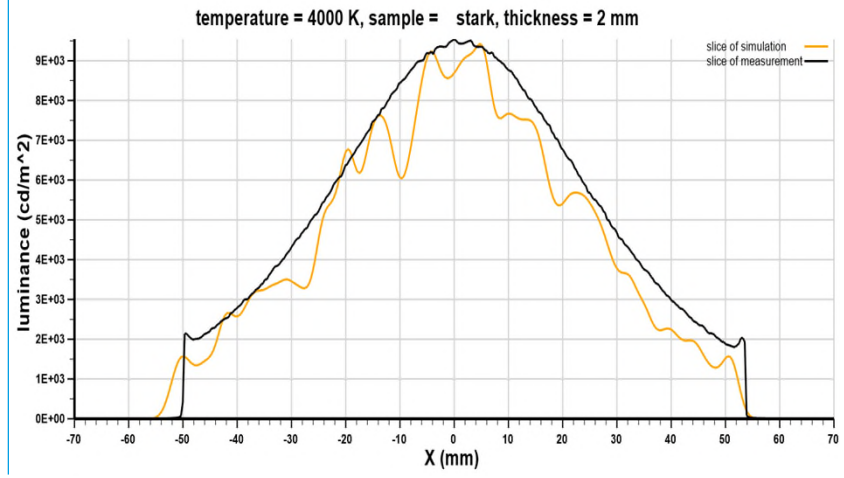












Summary

- **LED light often requires homogenization**
- **Volume diffusor can be tailor made for this application**
- **Simple characterization of volume diffusor is given by transmittance and HPA**
- **BTDF measurements are crucial to characterize volume diffusors**
- **For simulation we want provide validated optical material data**
- **With the aid of BTDF measurements and via parameter fitting we can evaluate the material data for volume diffusors to deliver input data for commercial software packages**

THANK YOU!

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