Freeform micro-optical elements on light management foils

EPIC Meeting on Advanced Microoptics: Simulation, Fabrication & Characterisation at Nanoscribe

May 11th 2022 13:15 - 13:45

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JOANNEUM RESEARCH
MATERIALS

JOANNEUM RESEARCH MATERIALS

FACTS & FIGURES

As of: 2021

~500 Employees

6 Locations

- Graz
- Klagenfurt
- Niklasdorf
- Pinkafeld
- Weiz
- Vienna

3 Thematic Areas

3 Owners

- State of Styria (80.75 %)
- BABEG – Carinthian Agency for Investment Promotion and Public Shareholding (14.25 %)
- Landesholding Burgenland GmbH (5 %)

7 Research Units

JOANNEUM RESEARCH MATERIALS

FACTS & FIGURES
As of: 2020

> 500 R&D-Projekts

19 Equity Holdings (as of 2021)

~ 50 Mio. EUR Research performance

~ 71 Mio. EUR Total Assets

~4 Mio. EUR Investments

~ 170 Refereed Publications

~ 140 Scientific Lectures

> 70 Thesis (Bachelor, Master, Dissertation)

6 National und International Awards

22 Patents (9 granted, 13 pending)

MATERIALS
Organization, Structure of Research Groups

- Director:
  - Paul Hartmann

  Paul.Hartmann@Joanneum.at


- 5 Research Groups

  ~ 100 Employees

- 2 Locations in Styria / Austria
  - Weiz
  - Niklasdorf


- 1 Location in Burgenland
  - Pinkafeld

Hybrid Electronics and Patterning
Barbara Stadlober

Light and Optical Technologies
Christian Sommer

Laser and Plasma Processing
Wolfgang Waldhauser

Sensors and Functional Printing
Jan Hesse

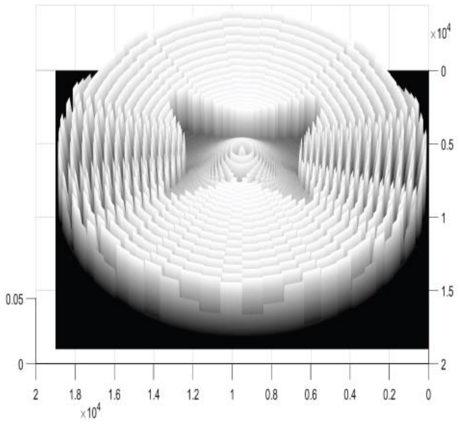
Smart Connected Lighting
Andreas Weiss

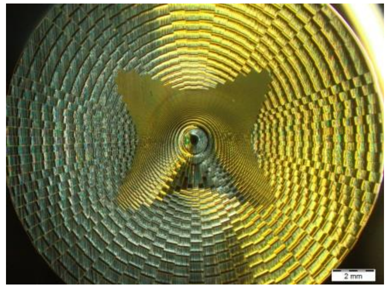
Light – for Function
and as a Tool

Light & Optical Technologies

Optics

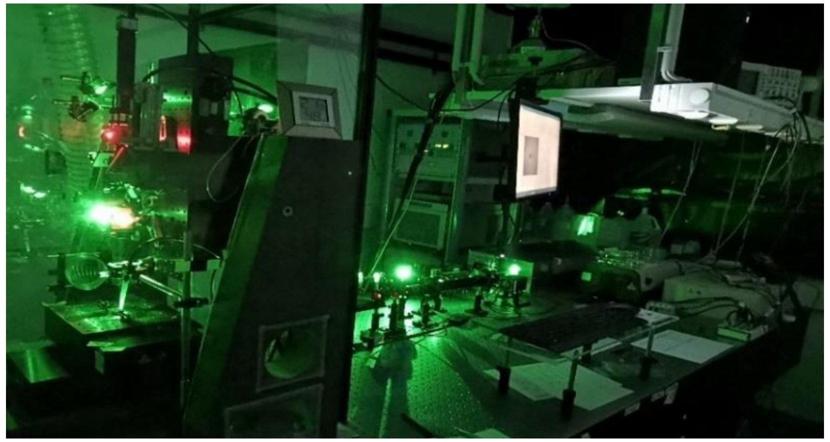
- **Optical simulation:** Ray-Tracing, Finite Difference Time Domain Method (FDTD), Multiscale Optical Simulations
- **Design, optimization of optical systems** for different applications (lighting, sensoric, photovoltaic)
- **Design of thin FF-optical elements for tailor made light management**





Laserprocessing

- **Laser ablation**: fabrication of ultraprecise mechanical and optical components, a.o.
- **Laser lithography:** two photon lithography, mastering of optical µ-structures
- **Laser sintering** of printed electrical contacts
- **Laser functionalization** of surfaces



PV & Optoelectronics

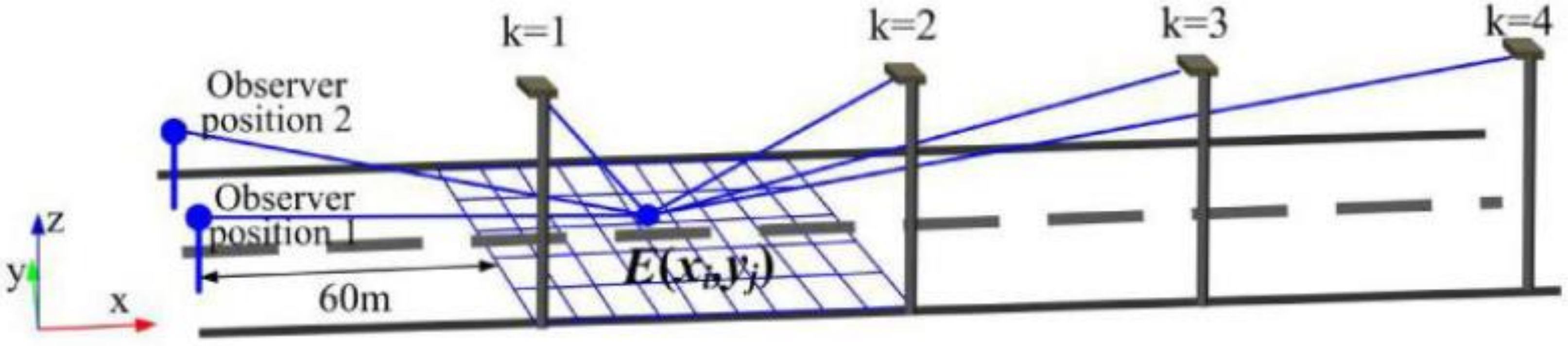
- **Common PV-Modules:** Innovative optical, photonic or plasmonic structures, Technologies for building integrated photovoltaics (BIPV)
- **Process and device development of next generation PV:** III-V semiconductors, OPV, Perovskites, CIGS, etc.
- **Development of methods:** for deposition and improving conductivity of printed electrical contacts
- **LED and LD technology** (phosphor conversion, lifetime models, reliability analyses, etc.)

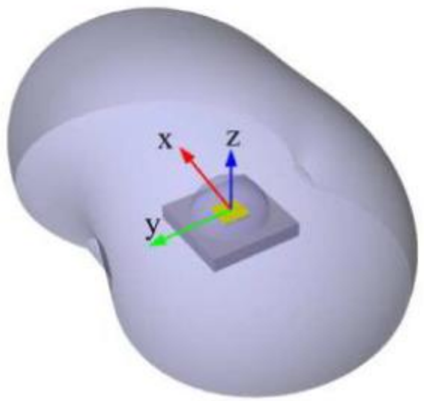
Introduction: Free-Form Optics

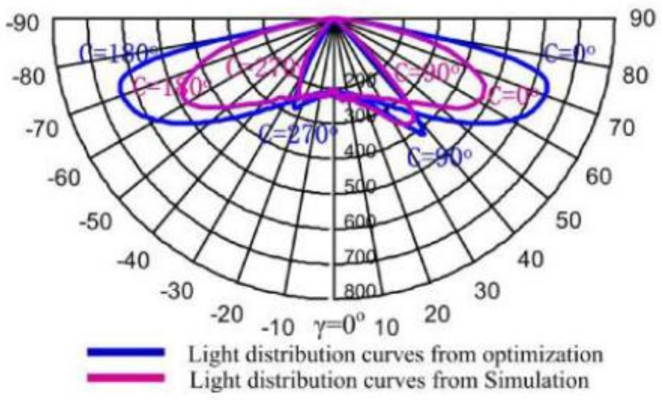
- Due to their nonrotational features, free-form optics can have almost an arbitrary surface and therefore offer incredibly high degrees of freedom compared to spherical optics.
- These high degrees of freedom e.g. allow the generation of tailored irradiance or radiant intensity distributions with a maximum of system performance or even combining the functionalities of different optical elements in one free-form surface.
- It’s not surprising that freeform optics has been a very hot topic of research and development over the last decades and has found wide application in many different fields.

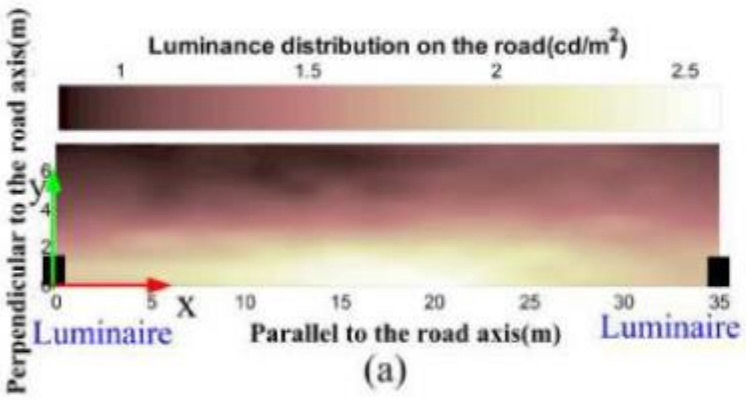
Introduction: Exemplary Application Fields of Free-Form Optics

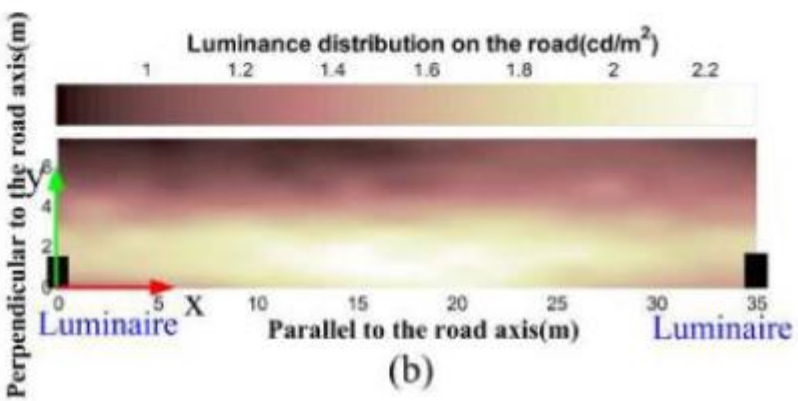
- Lighting







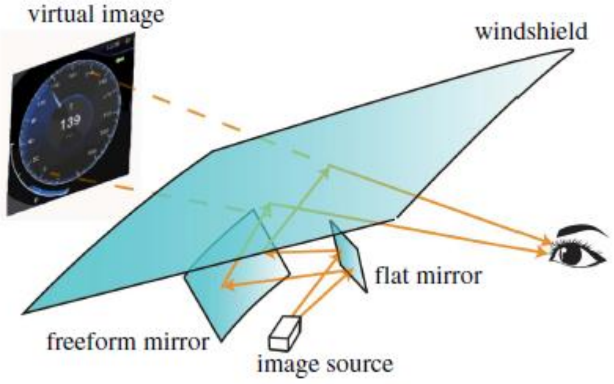


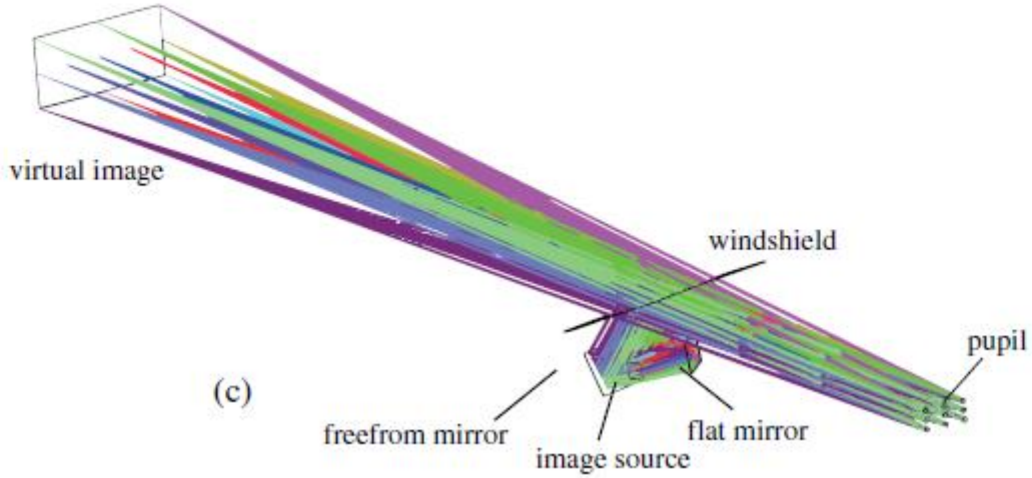


Feng, Z., Luo, Y., & Han, Y. (2010). Design of LED freeform optical system for road lighting with high luminance/illuminance ratio. *Optics express*, *18*(21), 22020-22031.

Introduction:
Exemplary Application Fields of Free-Form Optics

- Lighting
- Automotive





Wei, S., Fan, Z., Zhu, Z., & Ma, D. (2019). Design of a head-up display based on freeform reflective systems for automotive applications. *Applied optics*, *58*(7), 1675-1681.

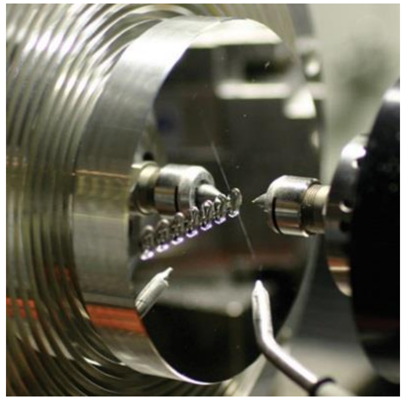
Introduction:
Exemplary Application Fields of Free-Form Optics

- Lighting
- Automotive
- VR and AR
- Imaging Systems
- Displays
- Optical sensors
- Telescopes
- Projectors
- Photovoltaics
- And many more

Motivation: Production of Free-Form Optics

- Conventional production methods of optics and freeform optics:
  - Creating a master with e.g.:

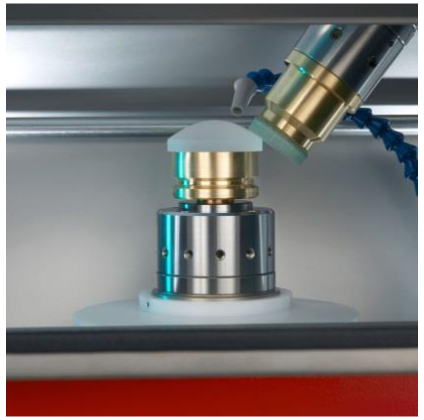
Diamond Turning



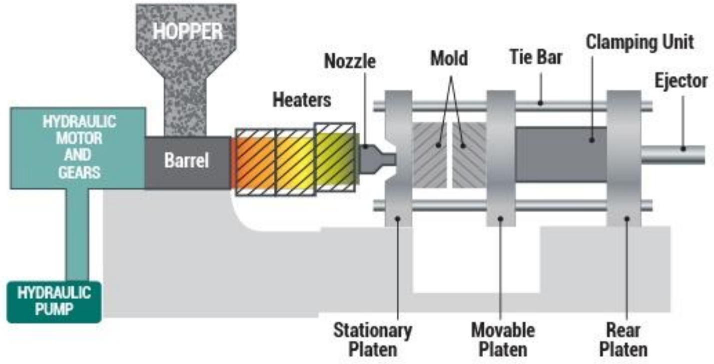
Milling

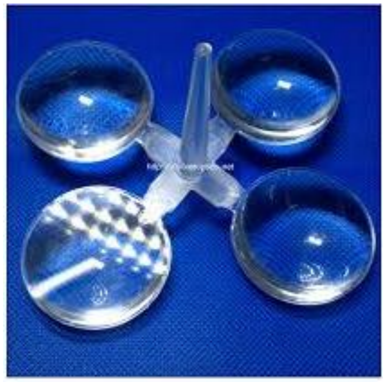
Grinding

Polishing



  - Replication of the master structure with injection molding :

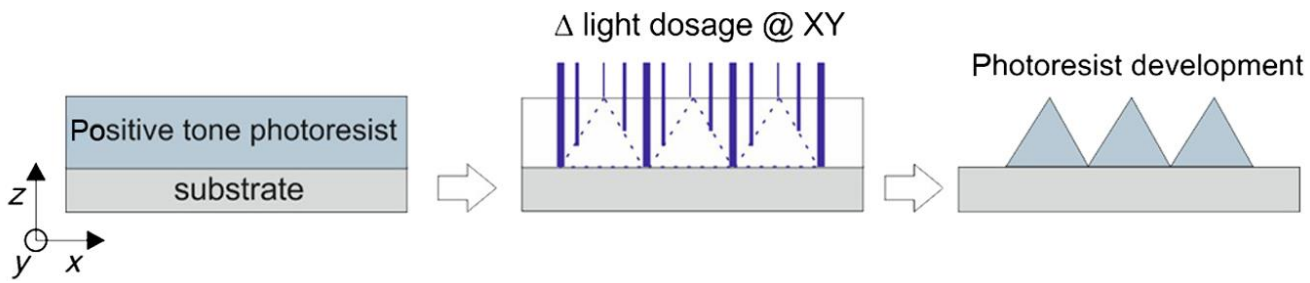




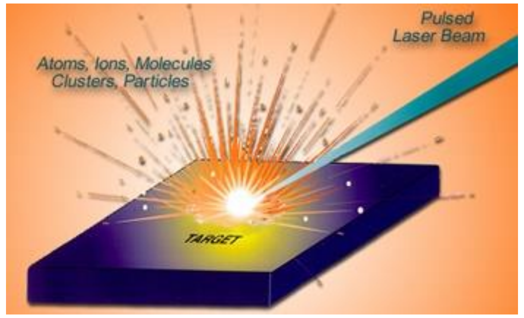
Motivation: „Why are FF-MOEs Interesting?“

- The low overall height of optical μ-structures also makes new production methods possible.
  - Masters can be created by direct laser writing methods:

Mask-less laser direct write lithography (1 or 2 Photon)



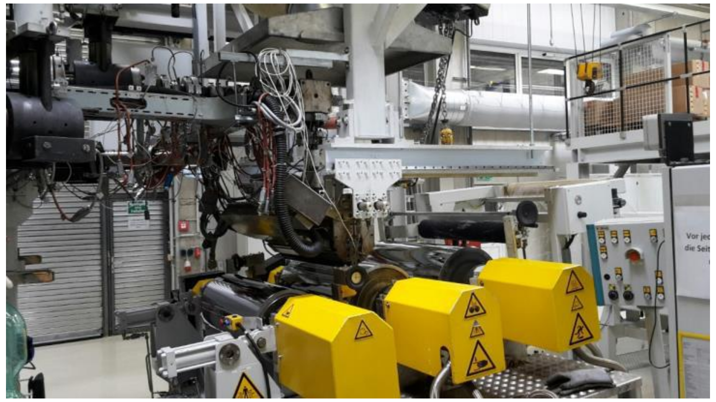
Laser-ablation for direct mastering



  - E.g. Replication of the master structures with:

Roll-To-Roll
UV Nanoimprint
Lithography

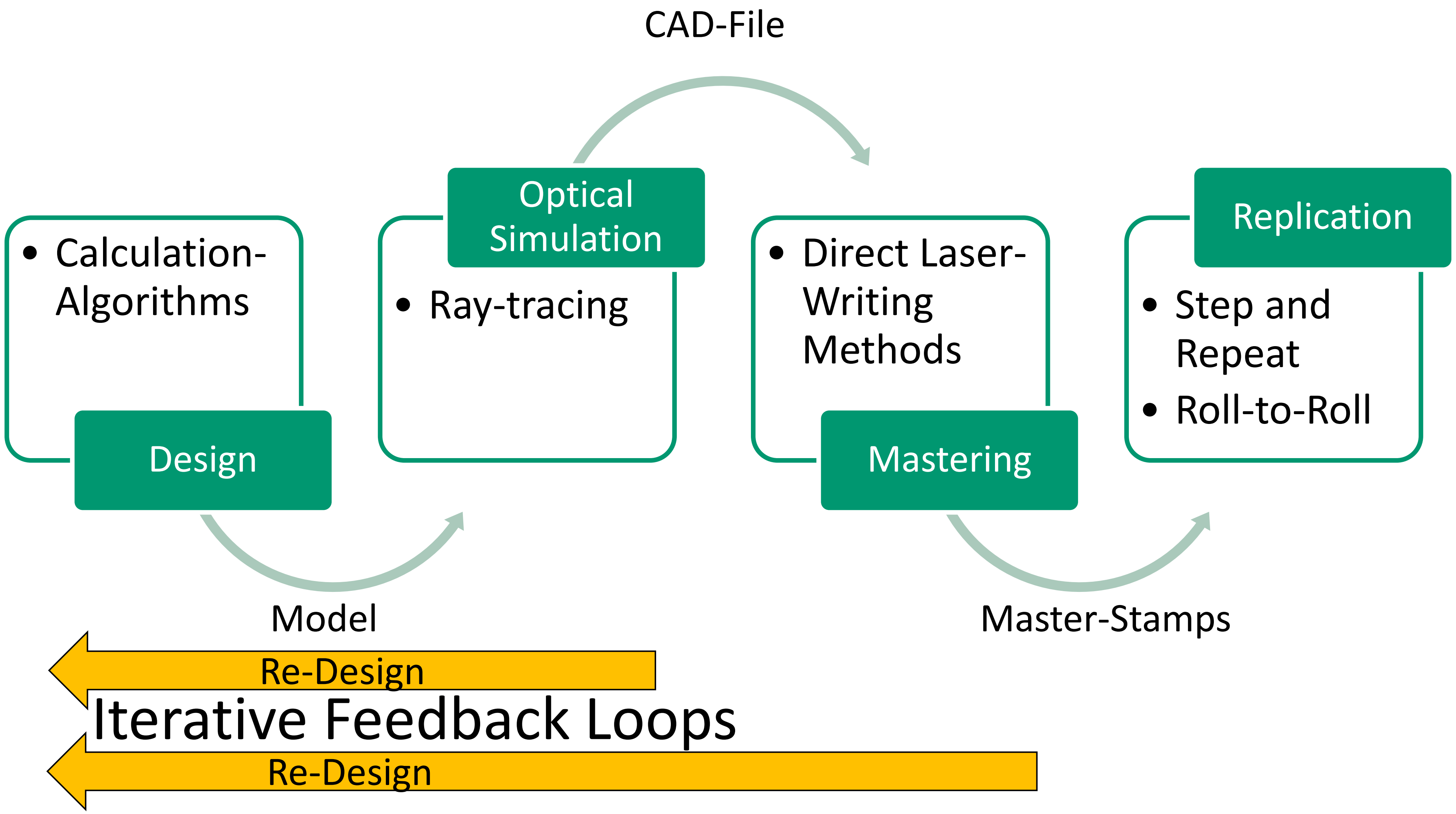
Foil-
Extrusion



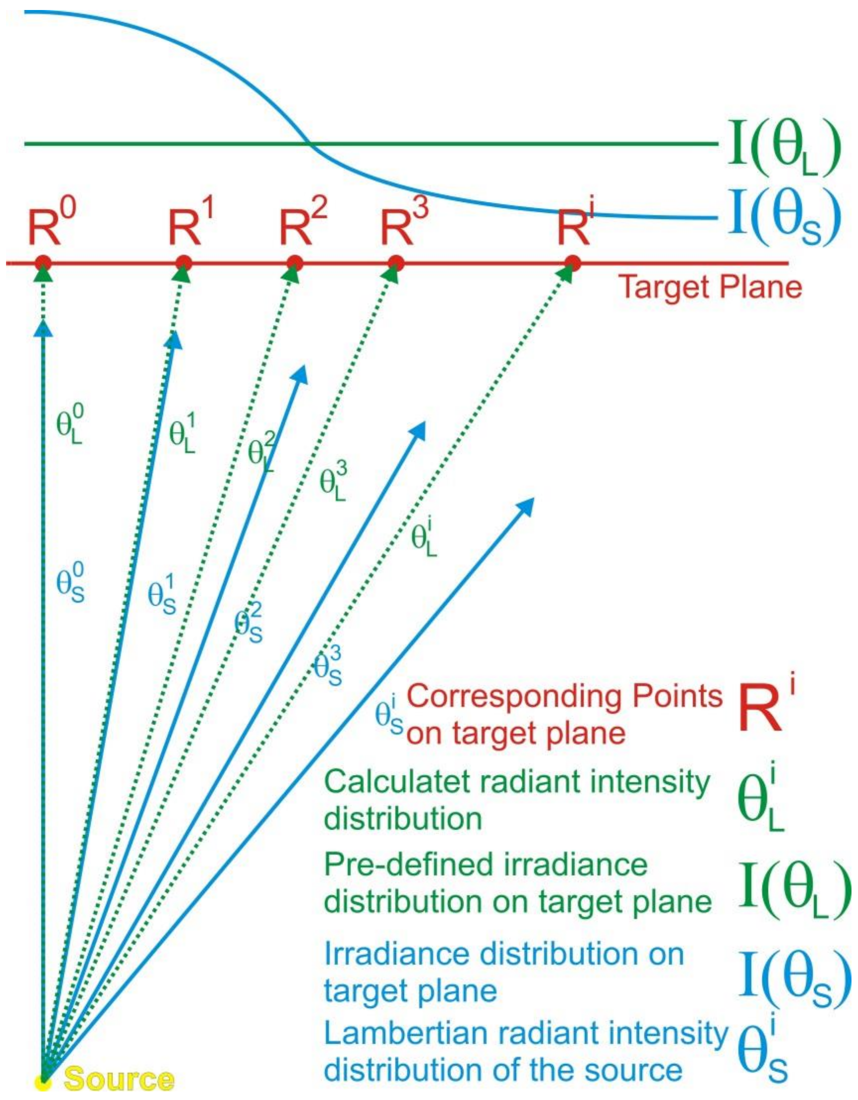
However to enable this, the Structures have to be flat (< 50 -200 μm)

Motivation: „Why are FF-MOEs Interesting?“

- Process chain in-house:



Explaining the approach of FF-MOEs Calculation - Raymapping



In the first step a point source with an angle dependent radiant intensity distribution (e.g. Lambertian) is illluminating a target plane located at a pre defined distance from the source.

The different rays from the source defined by their propagation angles θ_S are creating a non uniform irradiance distribution $I(\theta_S)$ on the target plane.

This irradiance distribution $I(\theta_S)$ has to be changed into a pre-defined irradiance distribution $I(\theta_L)$.

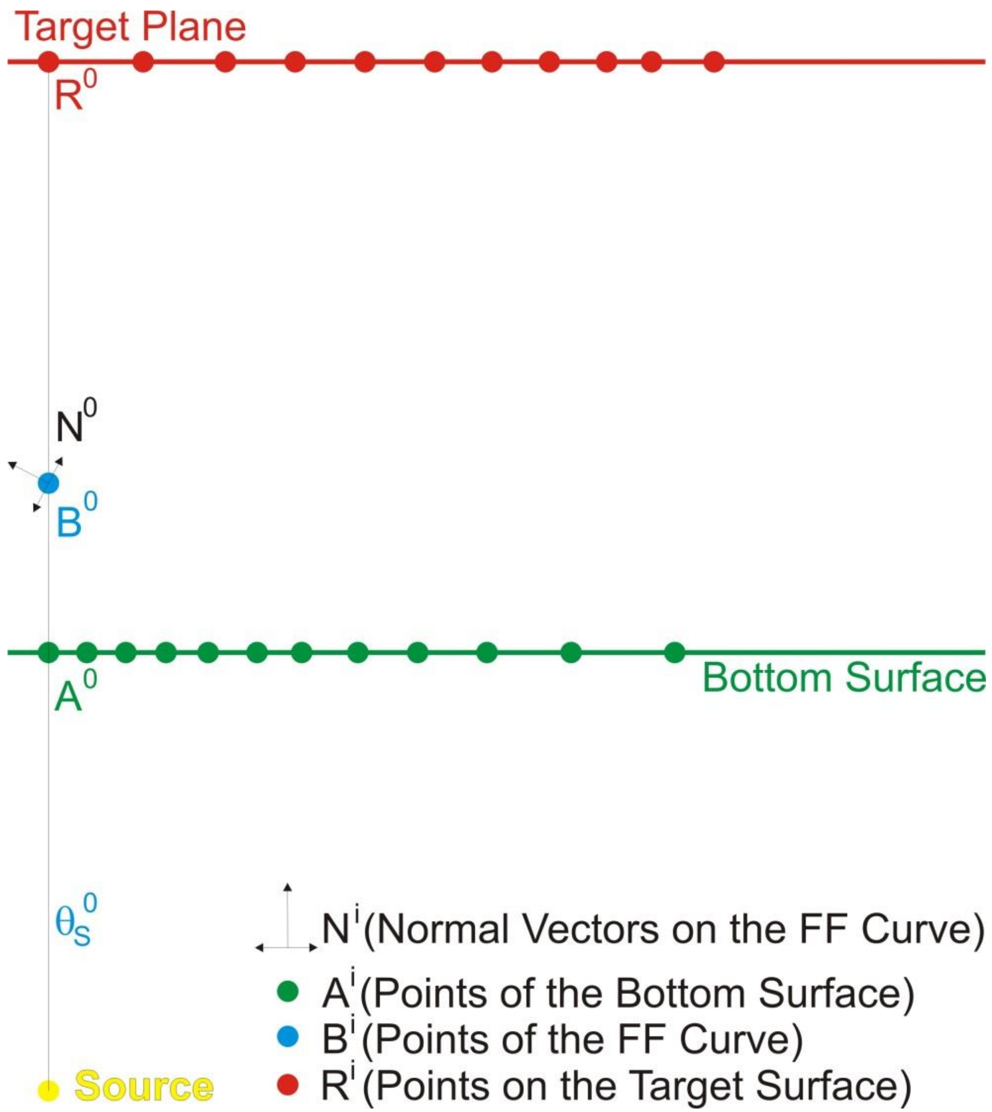
This can be achived by alternating the propagation angles qs of the rays emittet by the source into the propagation angles θ_L.

The radiant intensity distributions $I(\theta_L)$ and $I(\theta_S)$ are discretized into i rays with different propagation angles qLi and $\theta_S{}^i$

By assigning the rays with the angles $\theta_L{}^i$ on the target plane the points R_i can be determined

The pre-defined irradiance distribution on a target plane will be obtained by refracting the rays with angles $\theta_S{}^i$ through the FF surface towards their corresponding points R_i.

Explaining the Approach of FF-MOEs Calculation - Determining the FF Curves

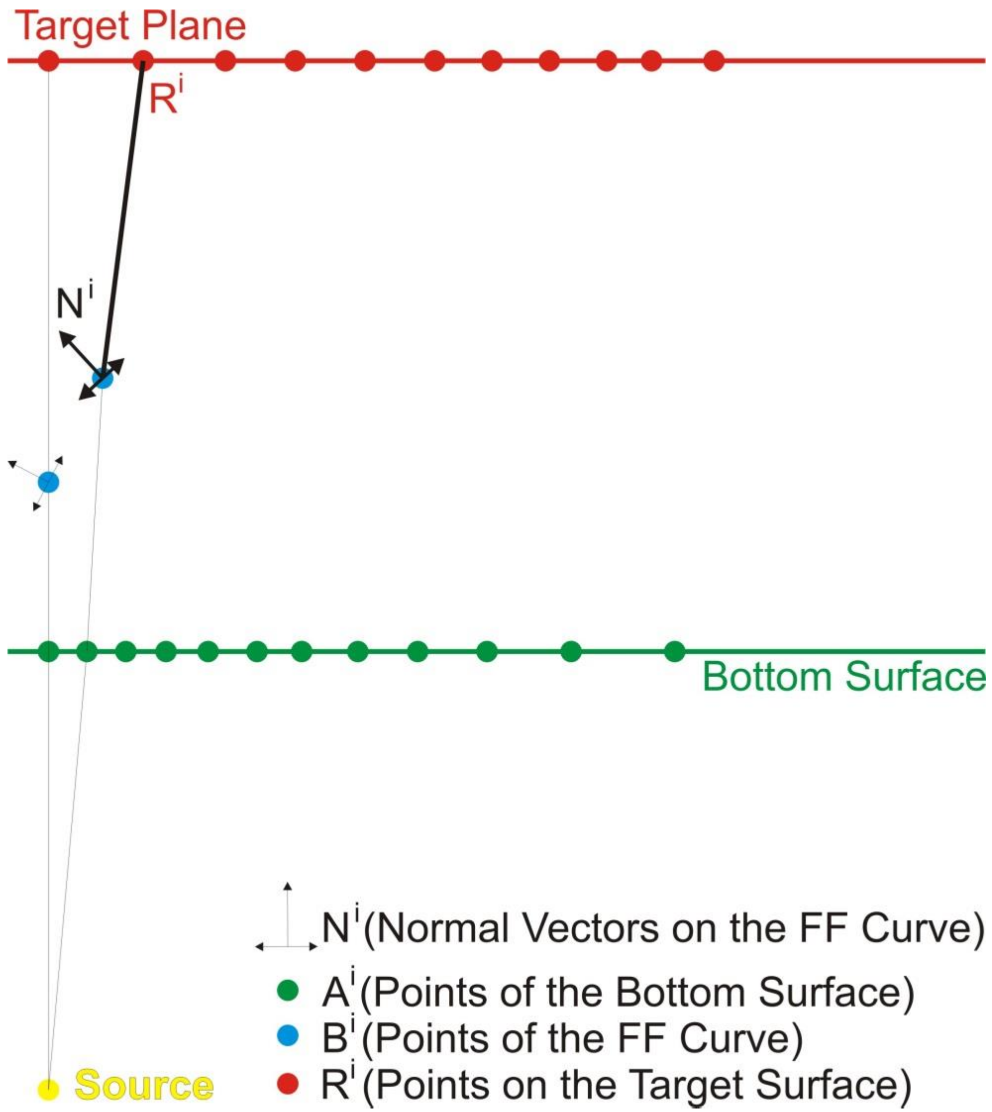


The two dimensional FF curve is calculated in a sequential process by calculating points on the surface B^i and the corresponding normal vectors N^i of the curve in these points B^i.

The points A^0 and B^0 are chosen freely to define the inertial thickness of the FF element. The normal vector N^0 is defined in a way that the ray with propagation angle $\theta_s{}^0$ is hitting the point R^0 on the target plane.

The next steps are repeated for every step **i** in a sequential manner

Explaining the Approach of FF-MOEs Calculation - Determining the FF Surface

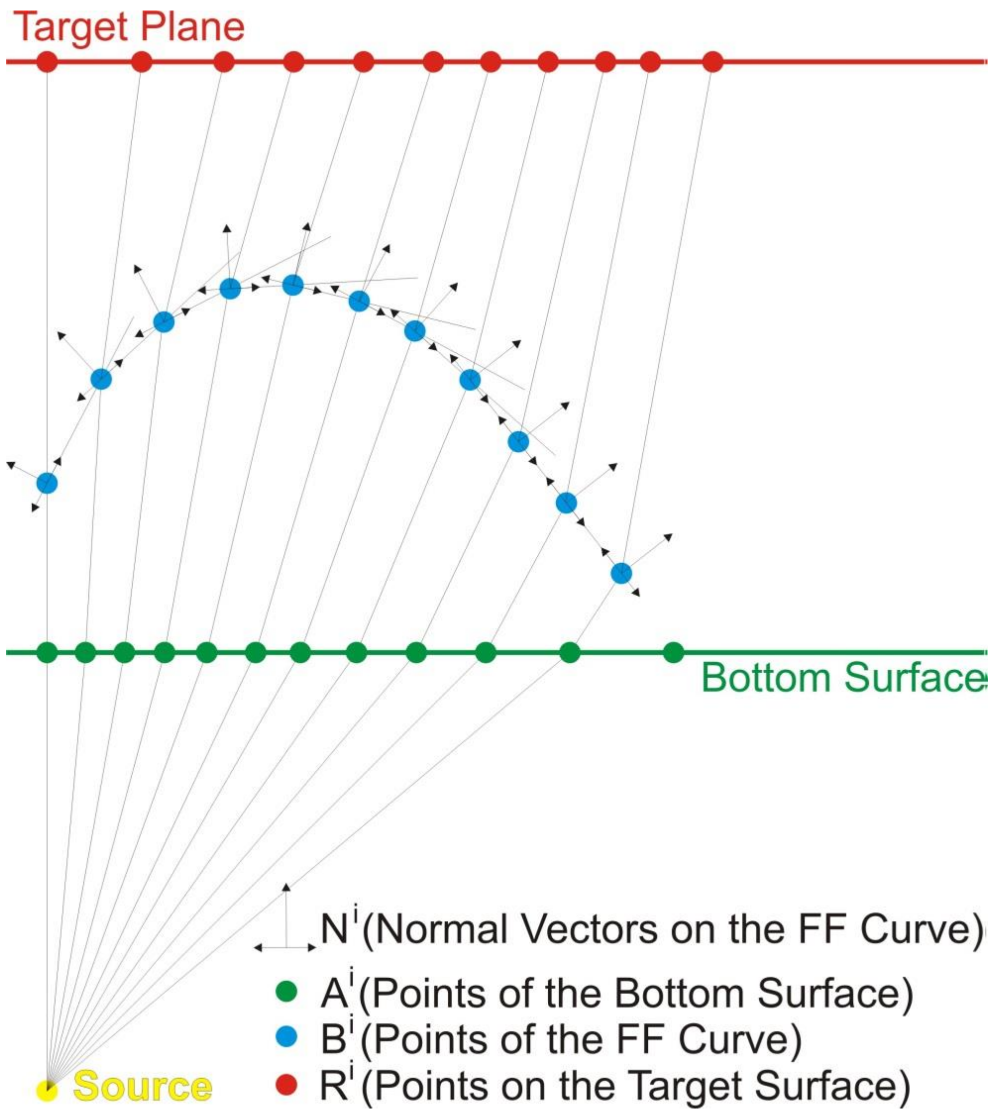


1.) The ray from the light source with the propagation angle θ_s^i is assigned to the point of intersection A^i of the bottom surface of the FF optic.

2.) The normal vector N^{i-1} and the corresponding tangent of the curve in point B^{i-1} are used to determine the new point B^i of the FF curve by intersecting the tangent with the direction of the i-th ray

3.) Snell's law defines the normal vector N^i of the point B^i in a way that the i-th ray is exactly refracted towards the point R^i on the target plane.

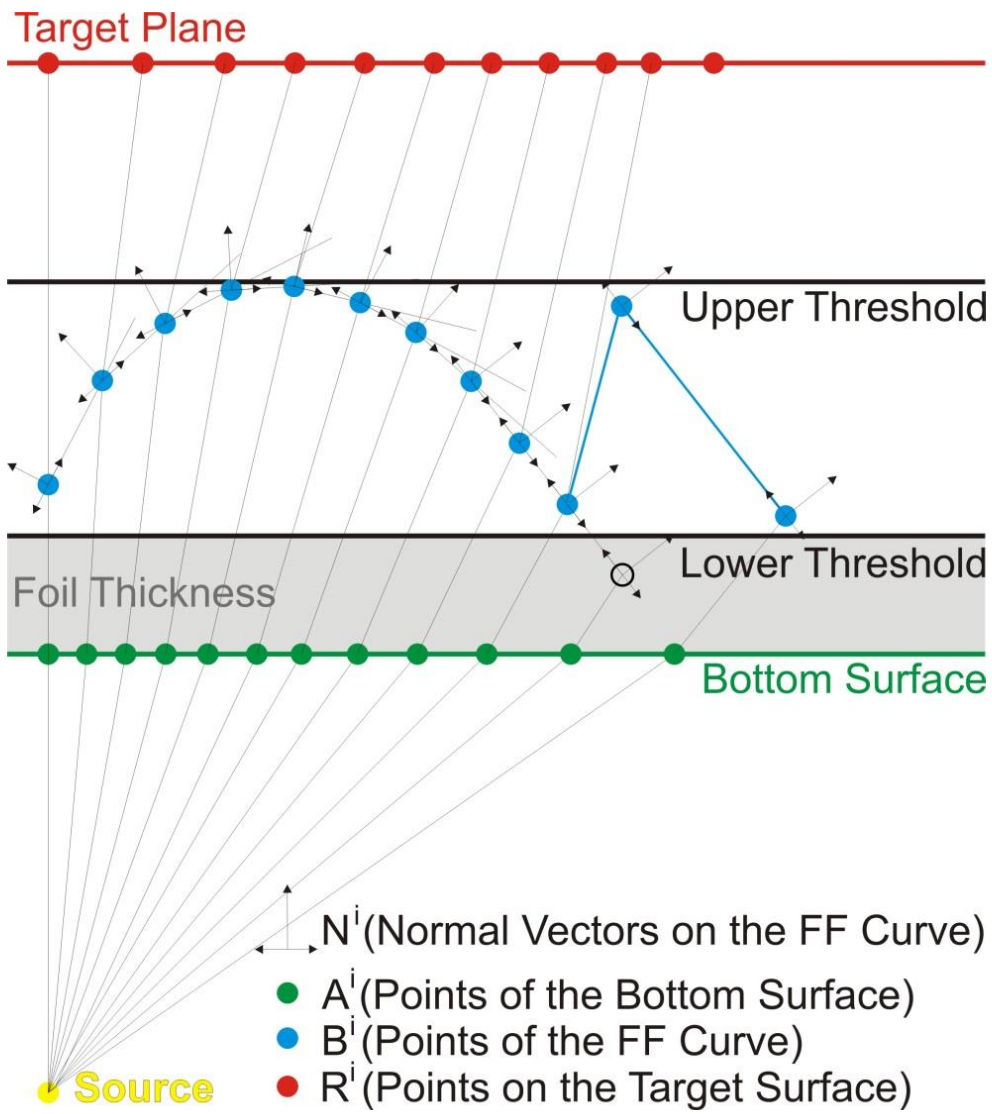
Explaining the Approach of FF-MOEs Calculation – Determining the FF Curves



Doing this step-by-step for each of the points A^i and B^i an optical FF curve is obtained.

However despite of the definition of the points A^0 and B^0, which can be chosen freely, the FF algorithm does not provide any possibilities to control the maximal height of the FF elements.

Explaining the Approach of FF-MOEs Calculation - Determining the FF Curves



Defining two threshold values for restricting the minimal and the maximal height of the B^i points

The distance between the lower threshold value and the bottom surface is defined by the thickness of the substrate foil.

When a point B^i of the FF curve drops below the lower threshold value and would be located inside the substrate foil, it is shifted upwards together with its corresponding normal vector N^i

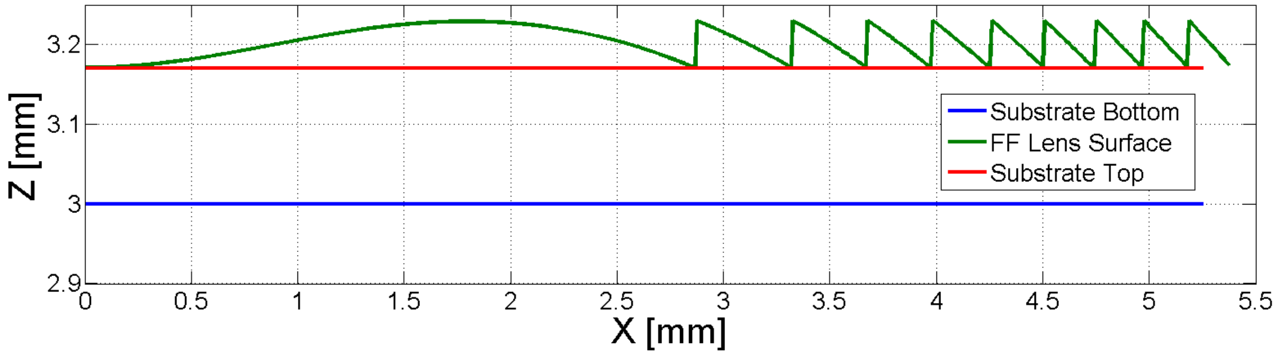
The shifted point B^i and its corresponding normal vector N^i are used subsequently to continue the sequence for calculating the next point B^{i+1}.

By this intervention two new straight lines are created in the FF curve.

Leiner, C., Nemitz, W., Wenzl, F. P., & Sommer, C. (2018). Ultrathin free-form micro-optical elements for direct-lit applications with a large distance-height ratio. *OSA Continuum*, *1*(4), 1144-1157.

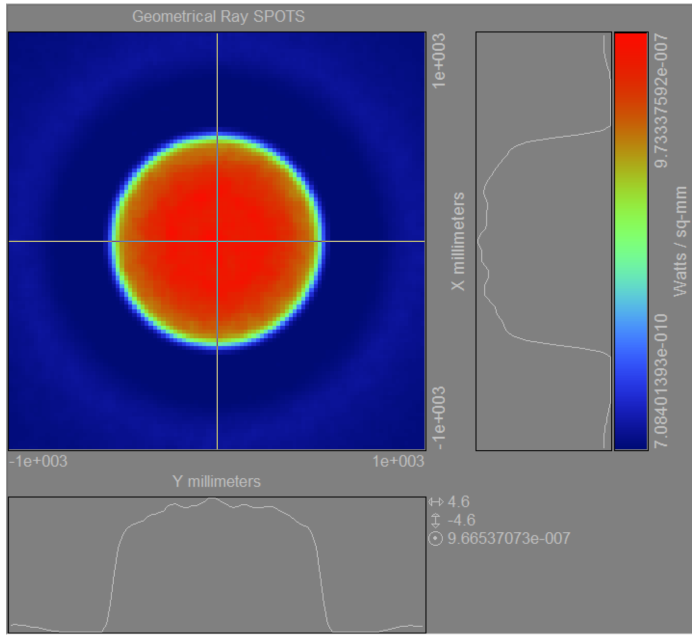
Explaining the approach of FF-MOEs
Example

Cross-section – FF curve

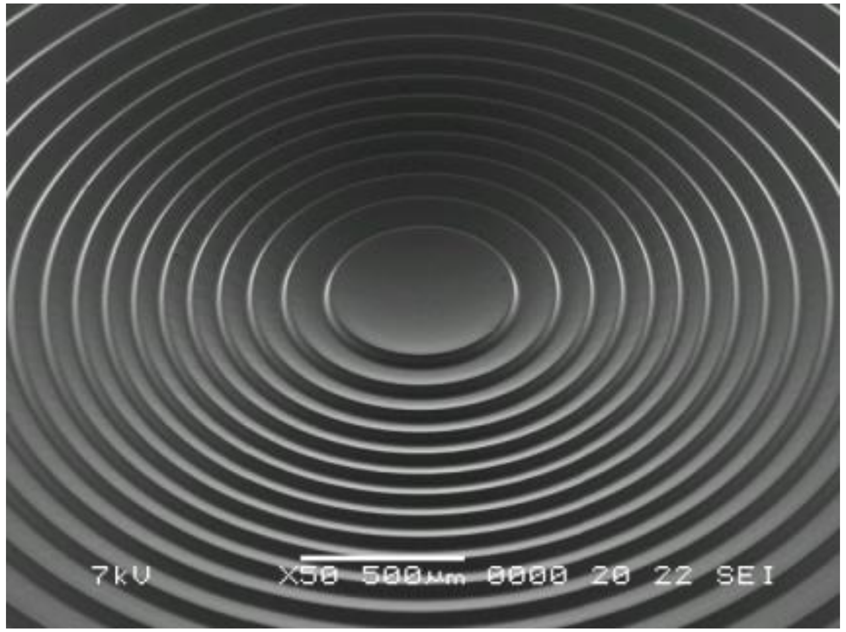


3D model of the optic

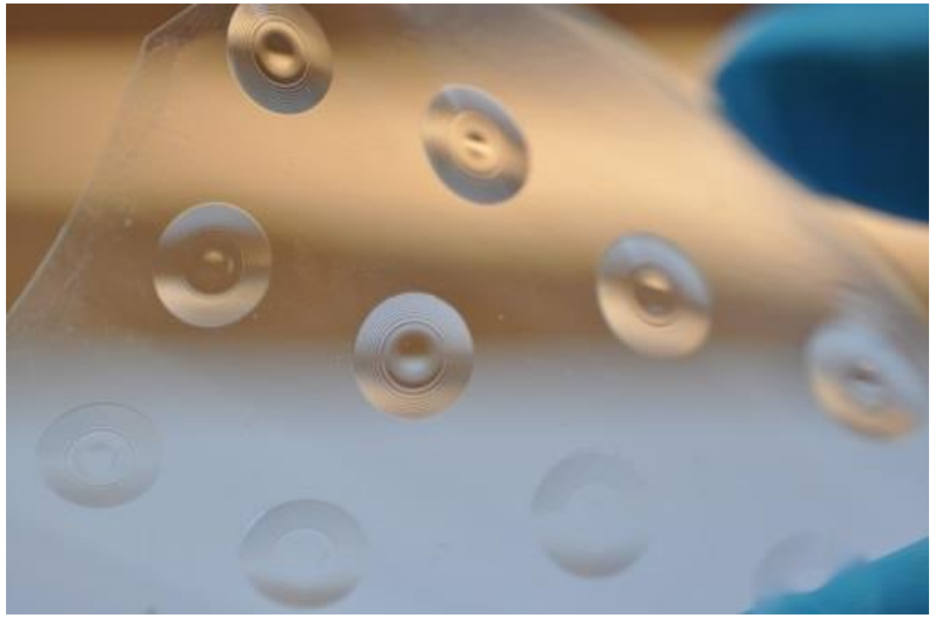
Simulated irradiance distribution



SEM picture of the master structure



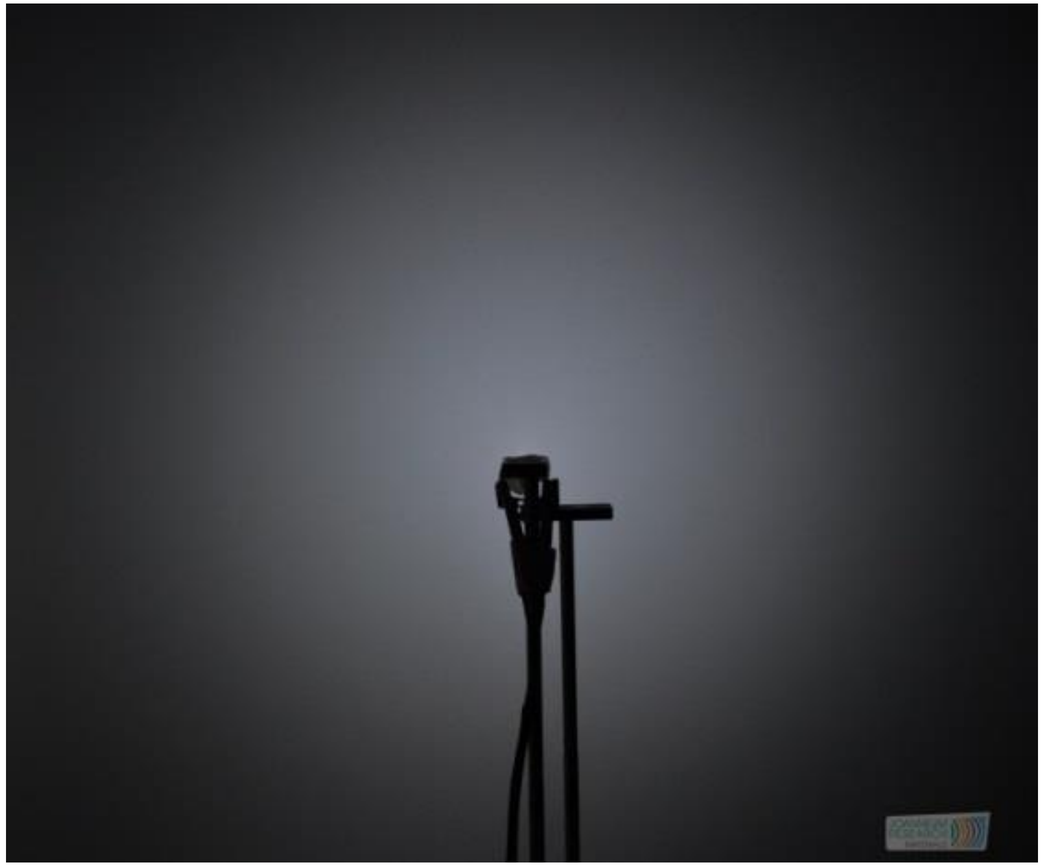
Optics on foil



Kuna, L., Leiner, C., Nemitz, W., Reil, F., Hartmann, P., Wenzl, F. P., & Sommer, C. (2017). Optical design of freeform micro-optical elements and their fabrication combining maskless laser direct write lithography and replication by imprinting. *Journal of Photonics for Energy*, *7*(1), 016002.

Explaining the approach of FF-MOEs Example

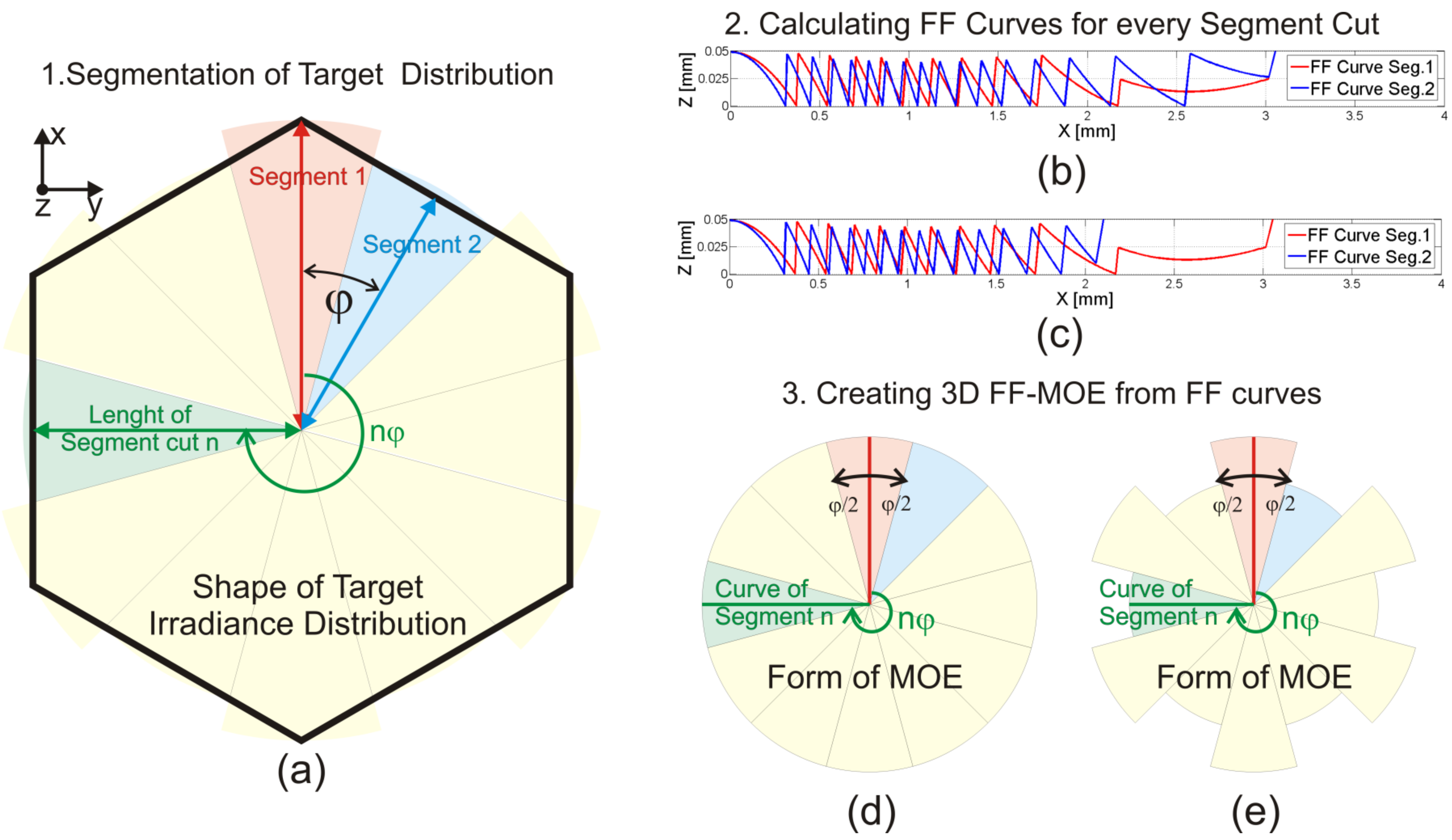
Irradiance Distribution on a target Wall



Without Structure

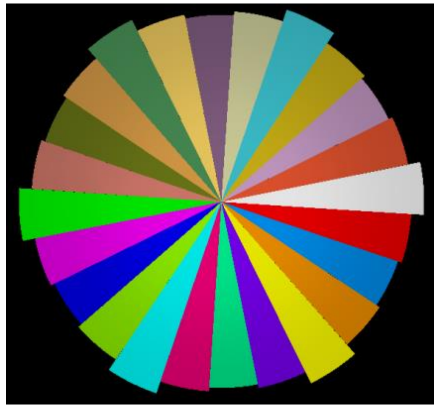
With Structure

Explaining the approach of FF-MOEs
Segmentation of FF-MOES

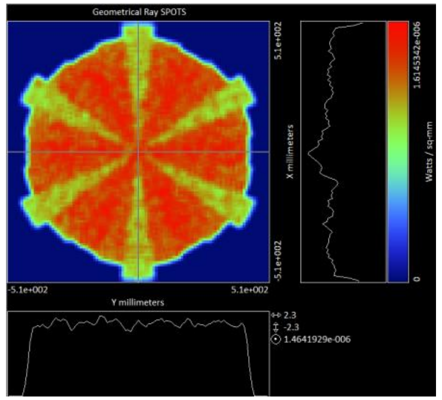


Explaining the approach of FF-MOEs Segmentation of FF-MOES

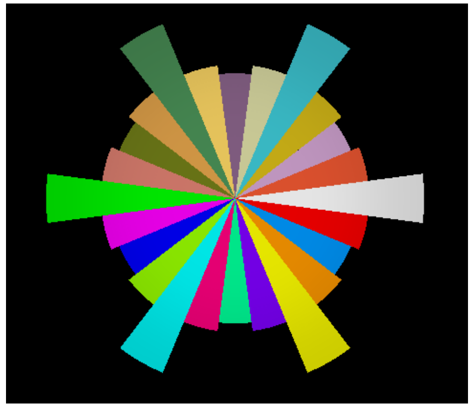
24 Segments



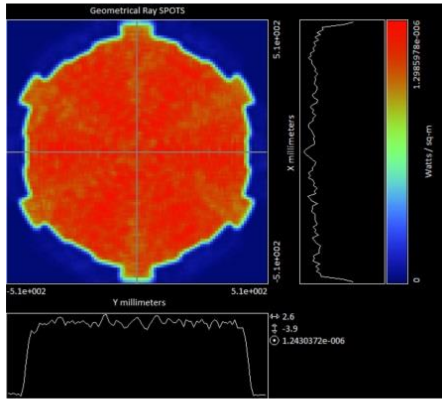
Irradiance distribution on the target plane



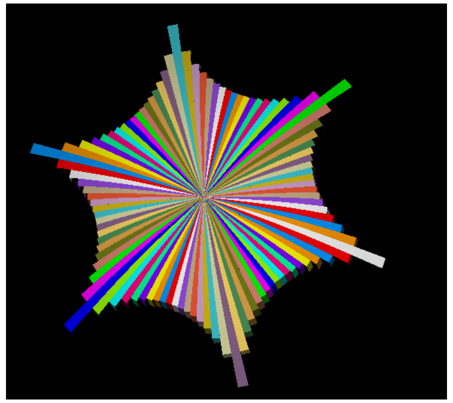
24 Segments
Adapted length of the slices



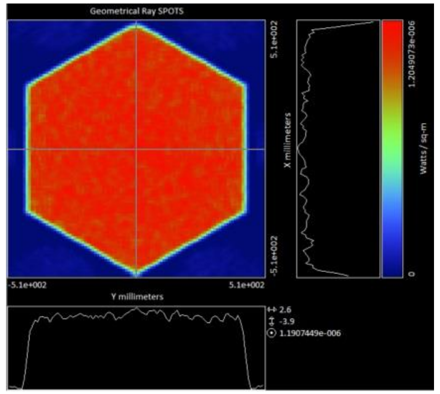
Irradiance distribution on the target plane



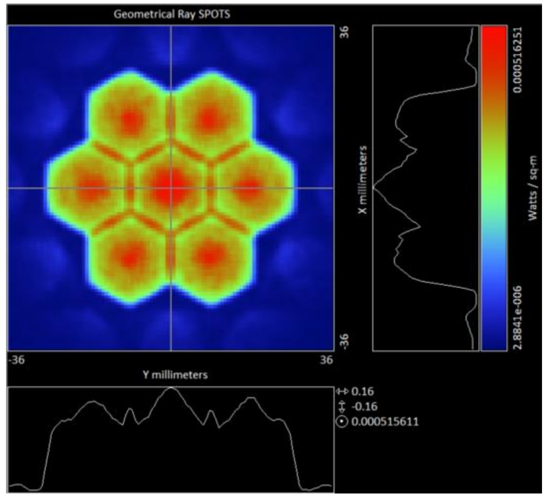
108 Segments,
Adapted length of the slices



Irradiance distribution on the target plane



Problem:
Non-captured light from the short slices of the FF-MOE



Solution:
Using additional structures to deflect non-captured light.
or
Including the influence of adjacent irradiance distributions if present.

Explaining the approach of FF-MOEs Segmentation of FF-MOES

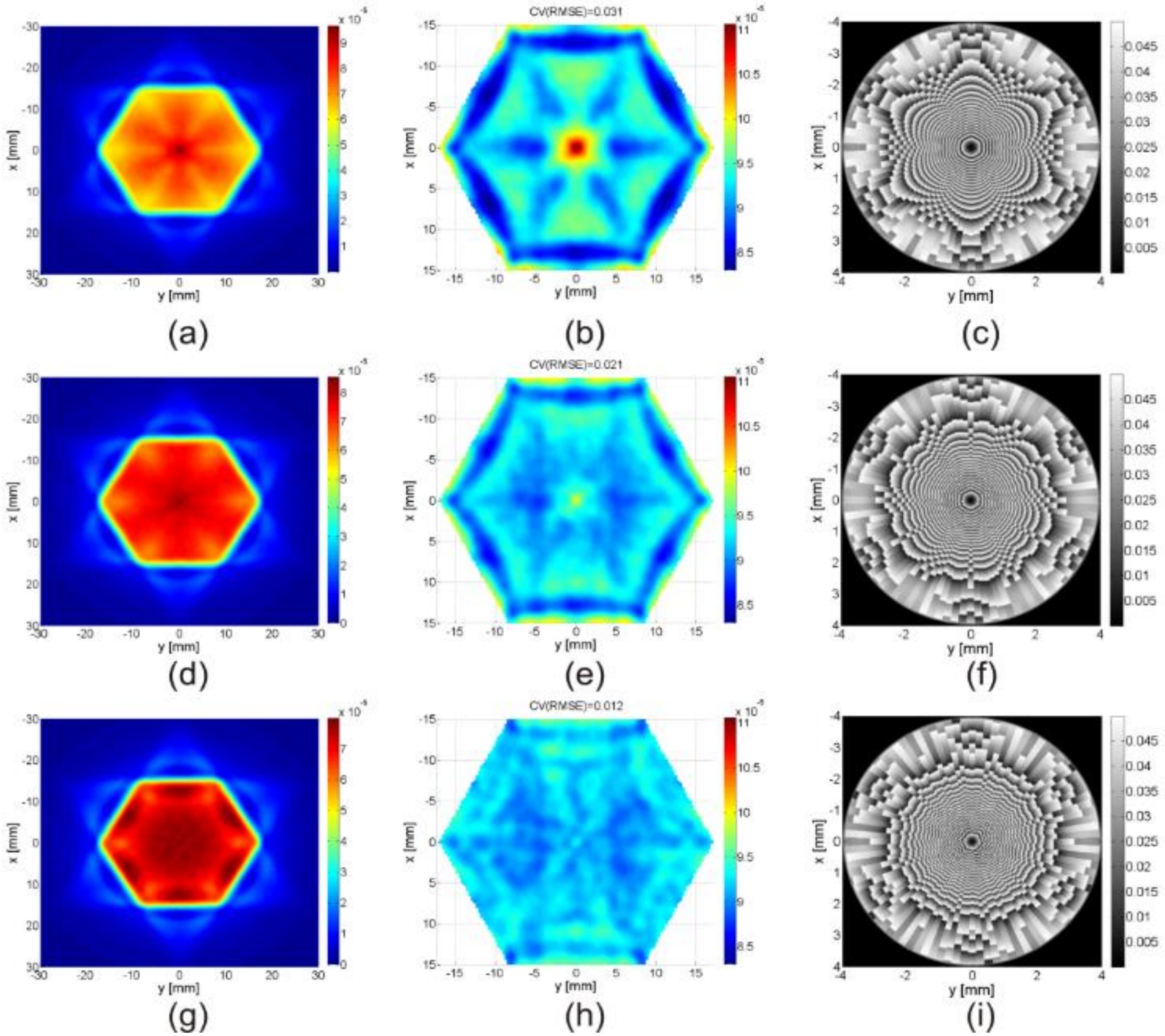
For including the influence of adjectand neighboring distributions an iterative ray-mapping process is used.

One cycle of this iterative algorithm is composed of 3 steps:

1) Calculating the FF-MOE based on the actual ray-mapping for every sector

2) Conducting a ray-tracing simulation with the current shape of the MOE

3) Determination of homogeneity deviations for each sector and conducting an adjustment of ray mapping for the next iterative cycle.



C. Leiner, W. Nemitz, S. Schweitzer, F. P. Wenzl and C. Sommer, "Design procedure for ultra-thin free-form micro-optical elements allowing for large DHR values and uniform irradiance distributions of ultrathin direct-lit luminaires." *OSA Continuum*, *3*(11), 3237-3252, (2020).

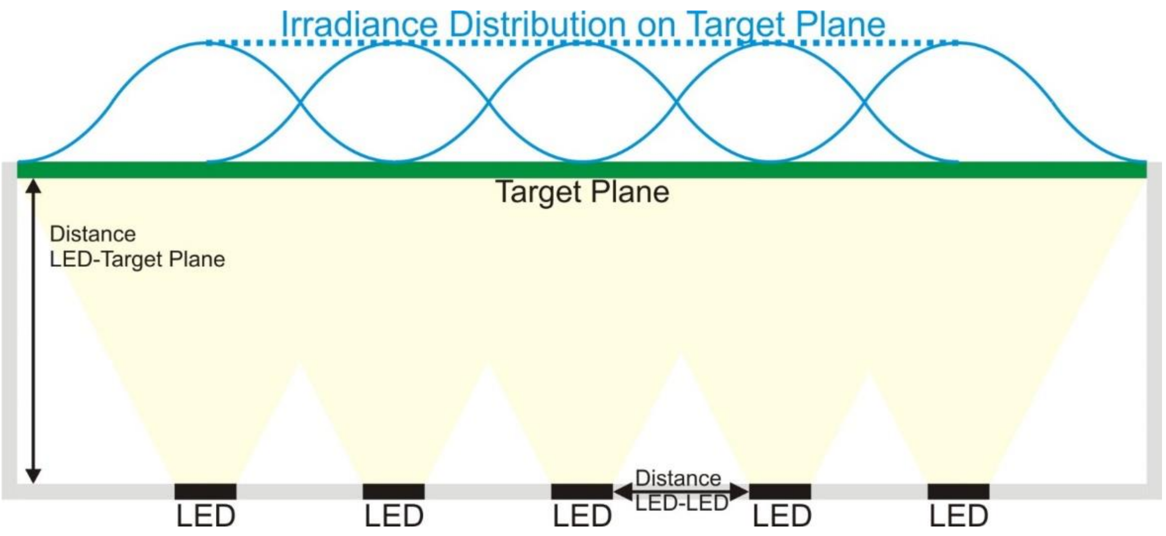
Application Example:
Linear direct-lit Luminaires

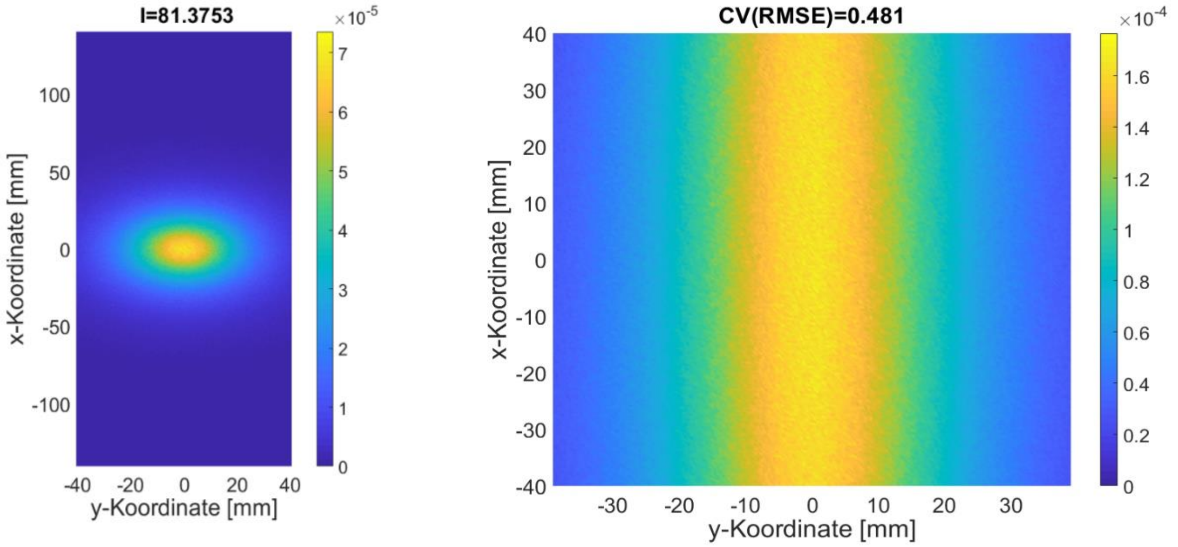
Phabulous

European Union's Horizon 2020 project for developing a pilot-line providing highly advanced & robust manufacturing technology for optical free-form mirco-structures

A detail of the interior concept design including the linear direct-lit LED luminaire.

Application Example: Optical System without FF-MOEs





Main Parameter of the System:

Distance LED - Target = 27.212 mm

Distance LED – LED

(same color-temperature) = **17.75 mm**

$$CV(RMSE) = \frac{\sqrt{\frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}(I(x_m, x_n) - I_{Mean})^2}}{I_{Mean}}$$

Raytracing simulation with 10 million rays:

Efficiency of the opt. sys. without diffusor: **~81.4 %**

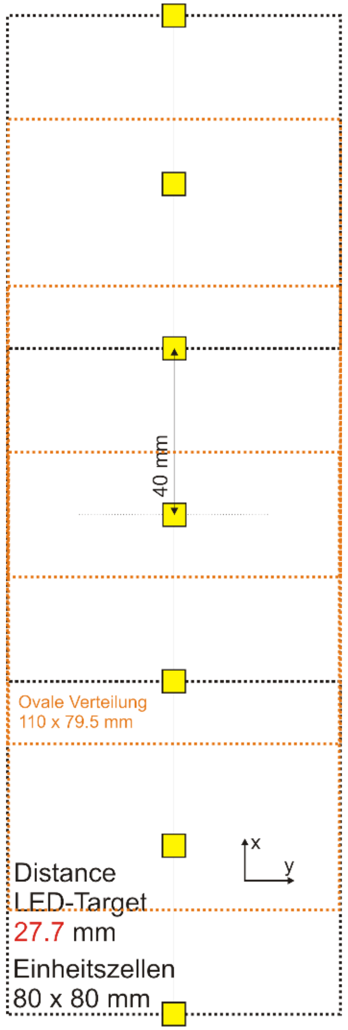
CV(RMSE) within 80 mm x 80 mm unit cell = **0.481**

A distance of 17.75 mm between the WW and the CW LEDs:

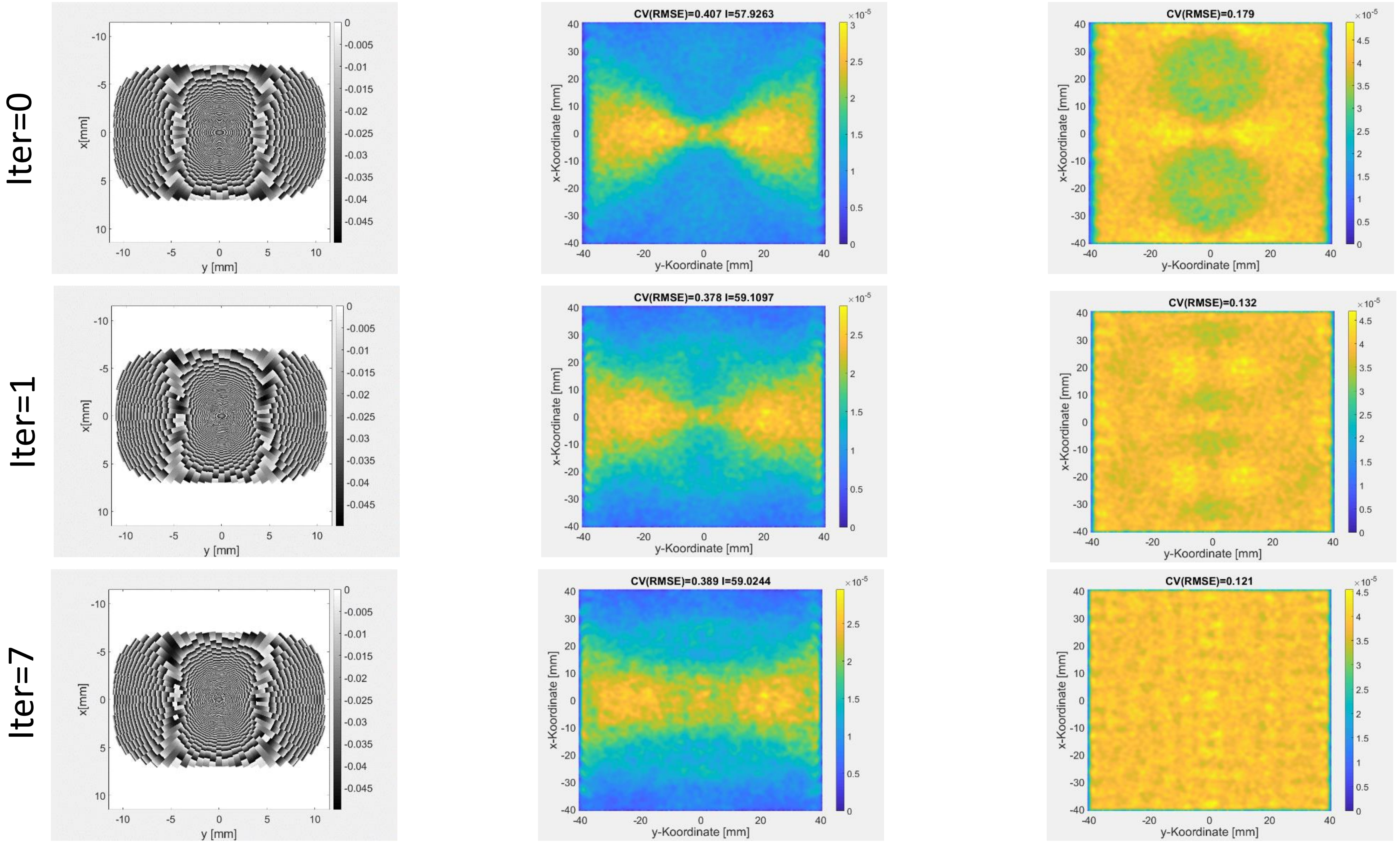
57 WW LEDs/m

57 KW LEDs/m

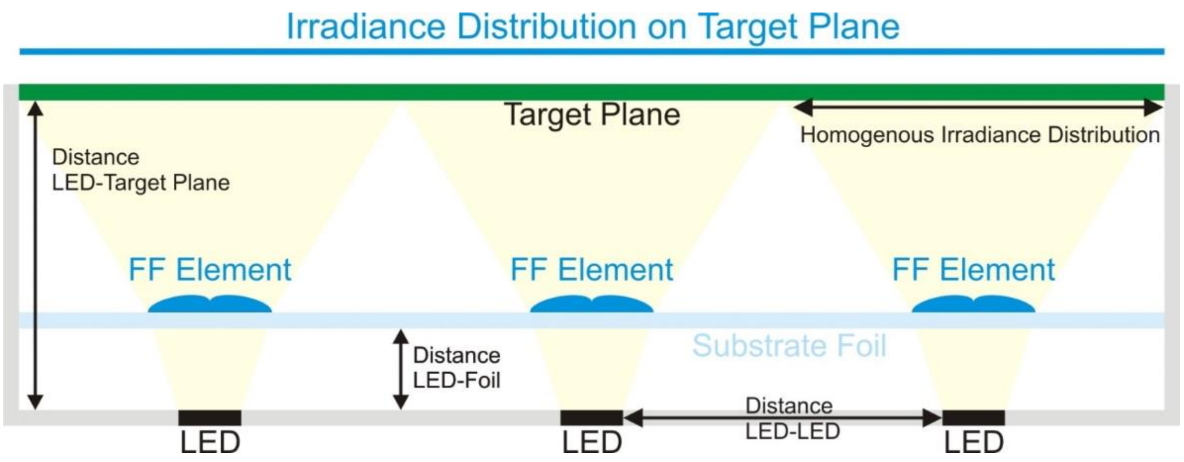
Application Example: Calculating FF-MOE for the System



FF-MOE Geometry | Irrad. Dist. Single Lens | Superposition



Application Example: Optical System with FF-MOEs



Raytracing simulation with 10 million rays:

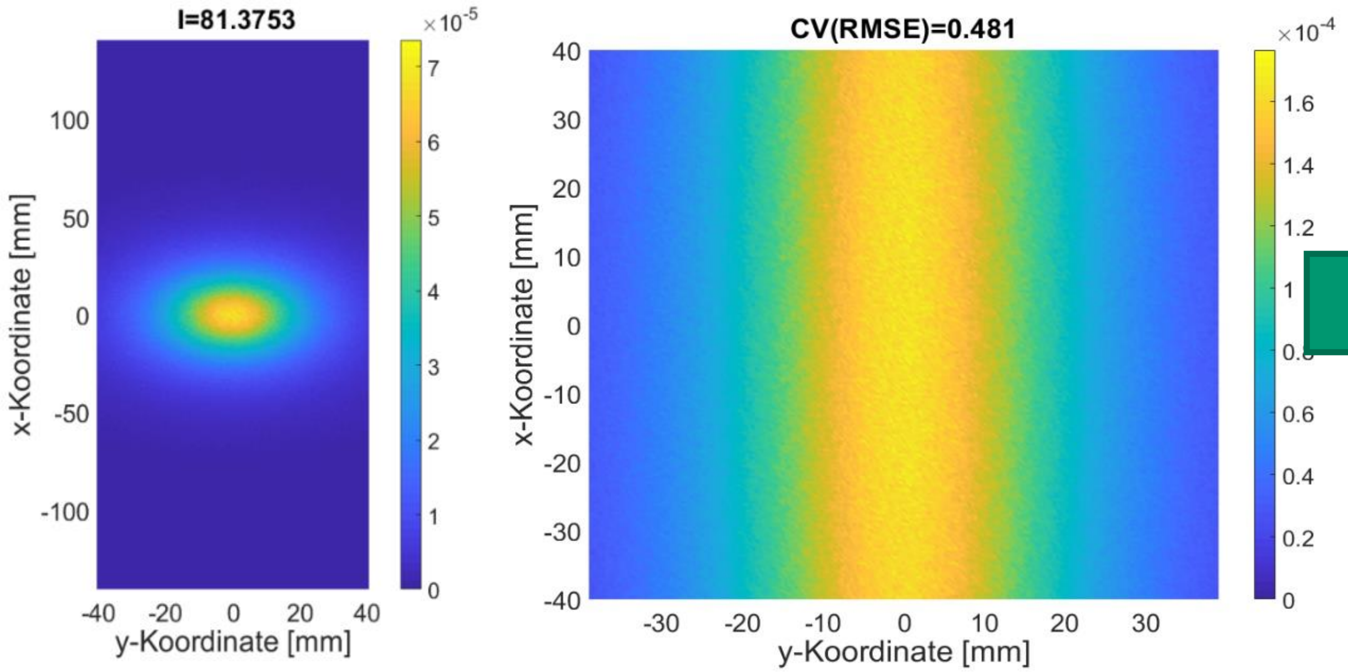
Efficiency of the opt. sys. without diffusor: **~81.4 % → 75.4%**

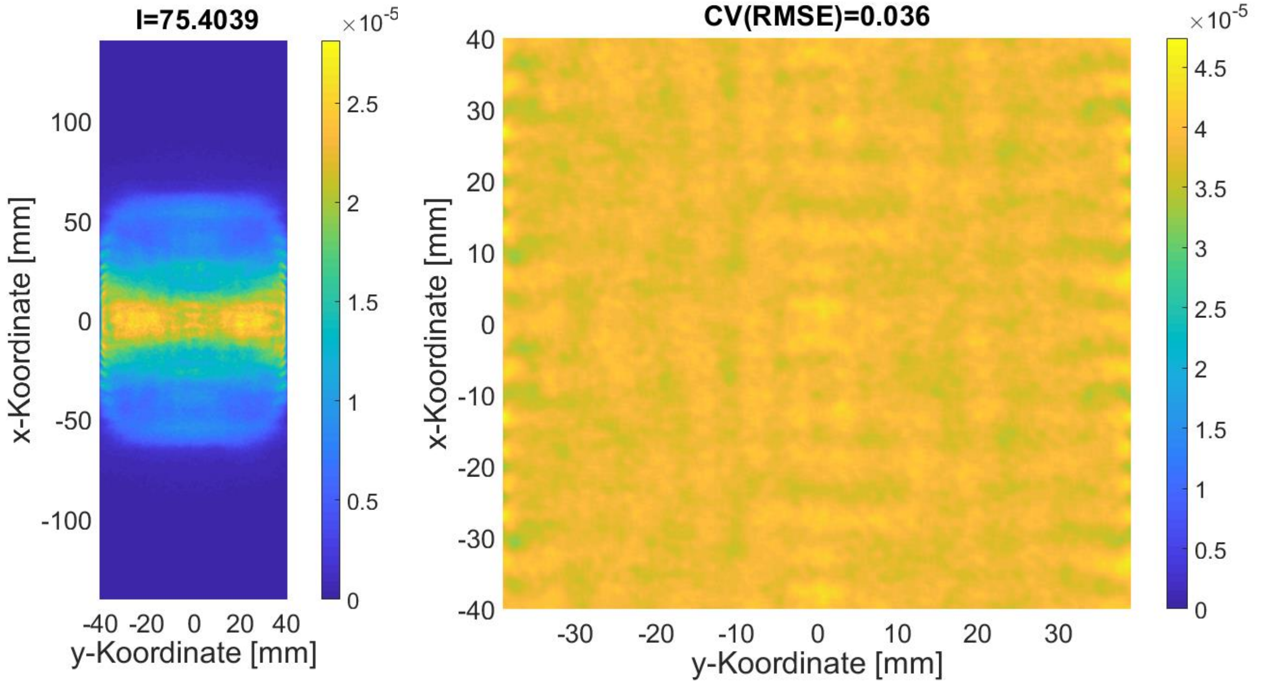
CV(RMSE) within 80 mm x 80 mm unit cell = **0.481 → 0.036**

Now a distance of 40 mm between the WW and the CW LEDs:

57 WW LEDs/m → 25 WW LEDs/m

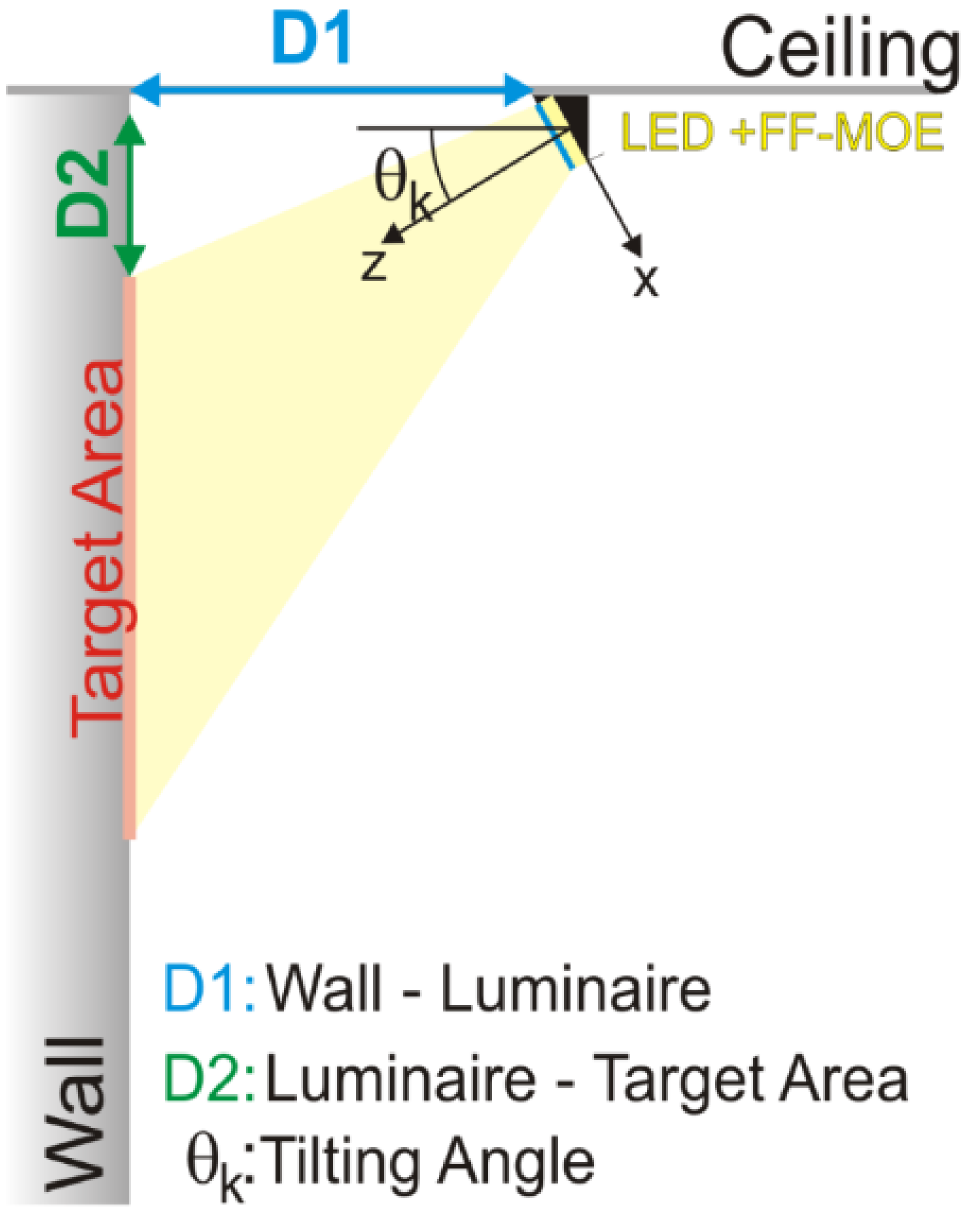
57 KW LEDs/m → 25 KW LEDs/m

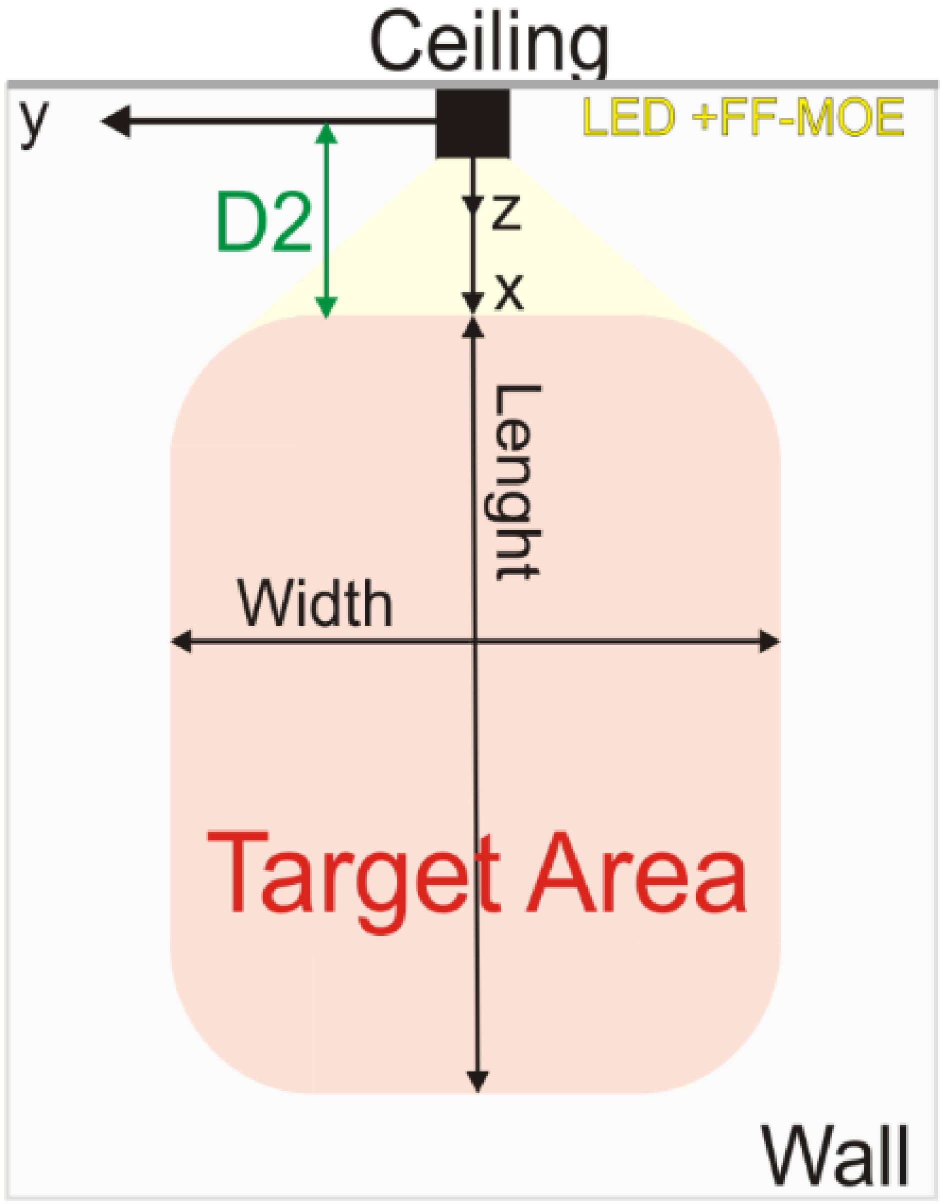




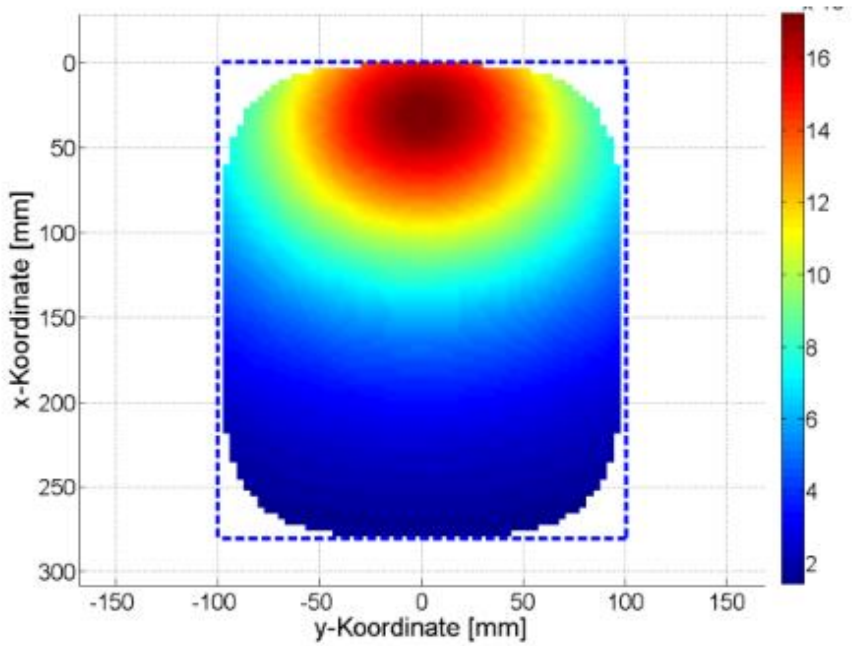
Application Example FF-MOES: Wall-Wash Luminaire

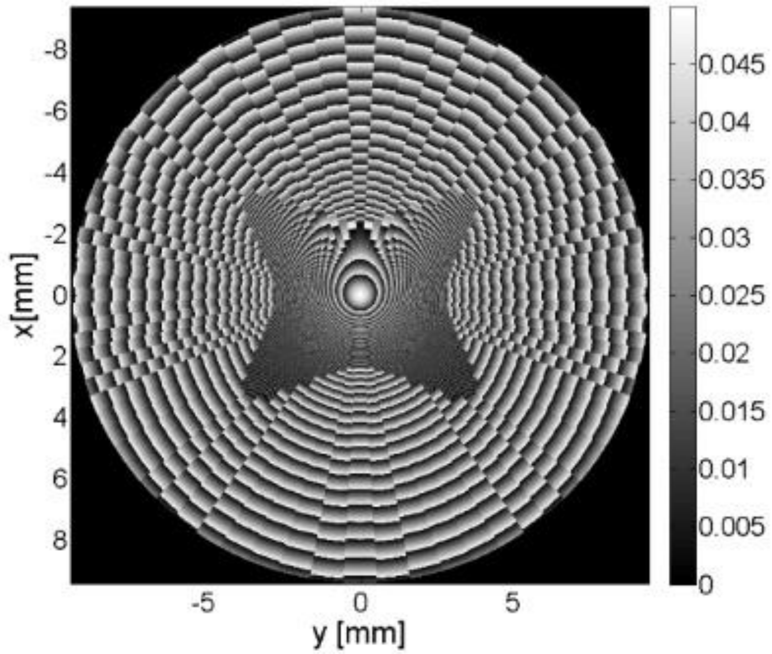
- Wall-wash application: An LED light source on the ceiling should homogeneously illuminate an oval target distribution on the wall.

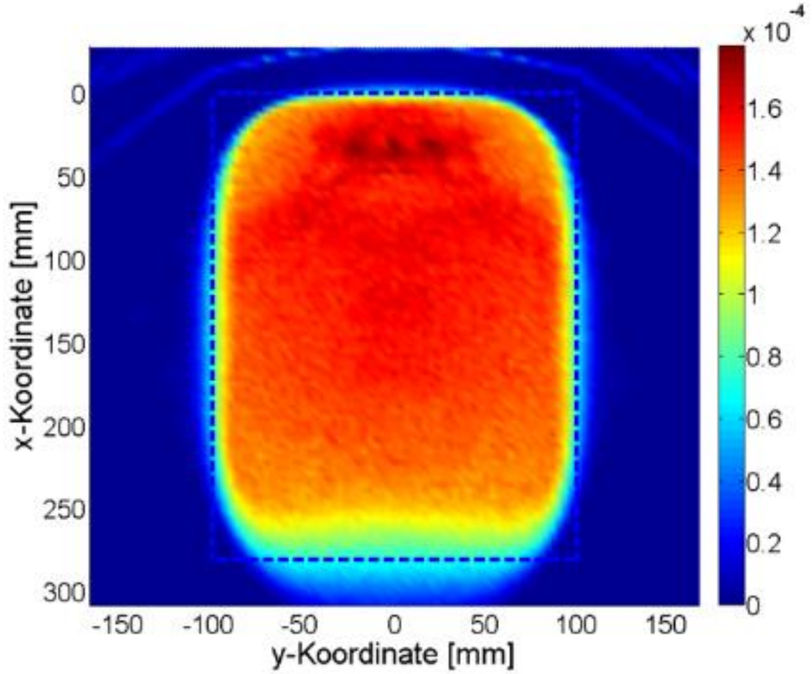


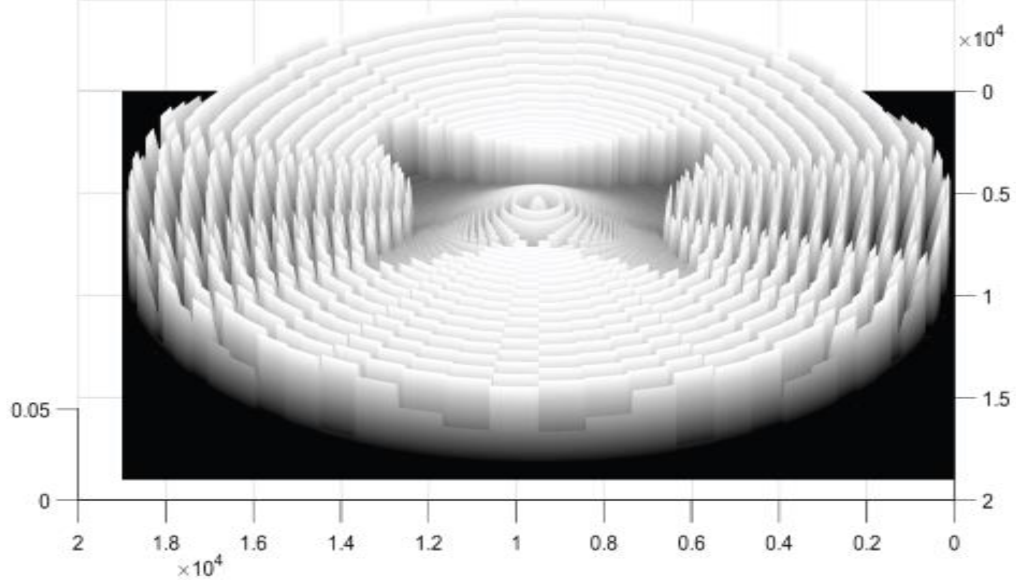


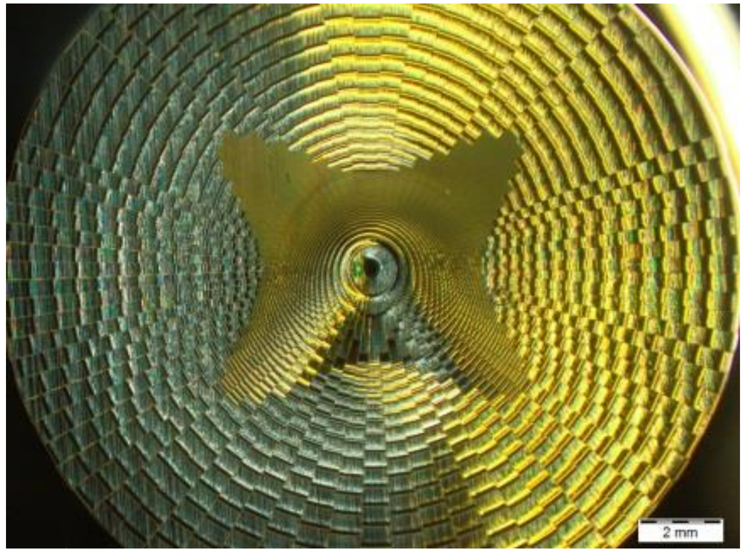
Application Example FF-MOES: Wall-Wash Luminaire











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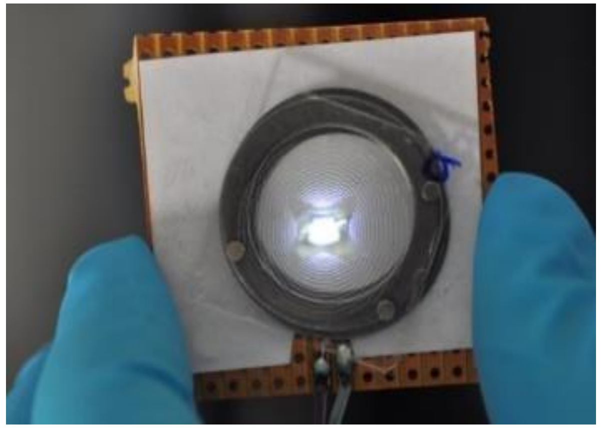
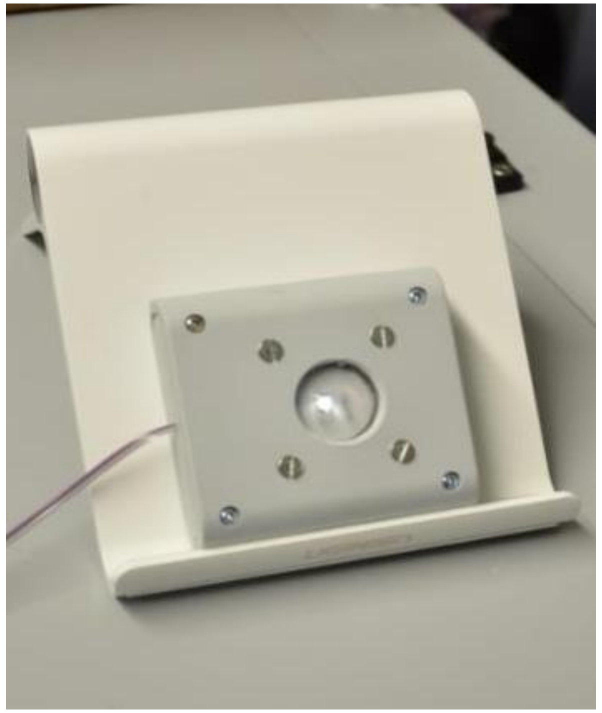
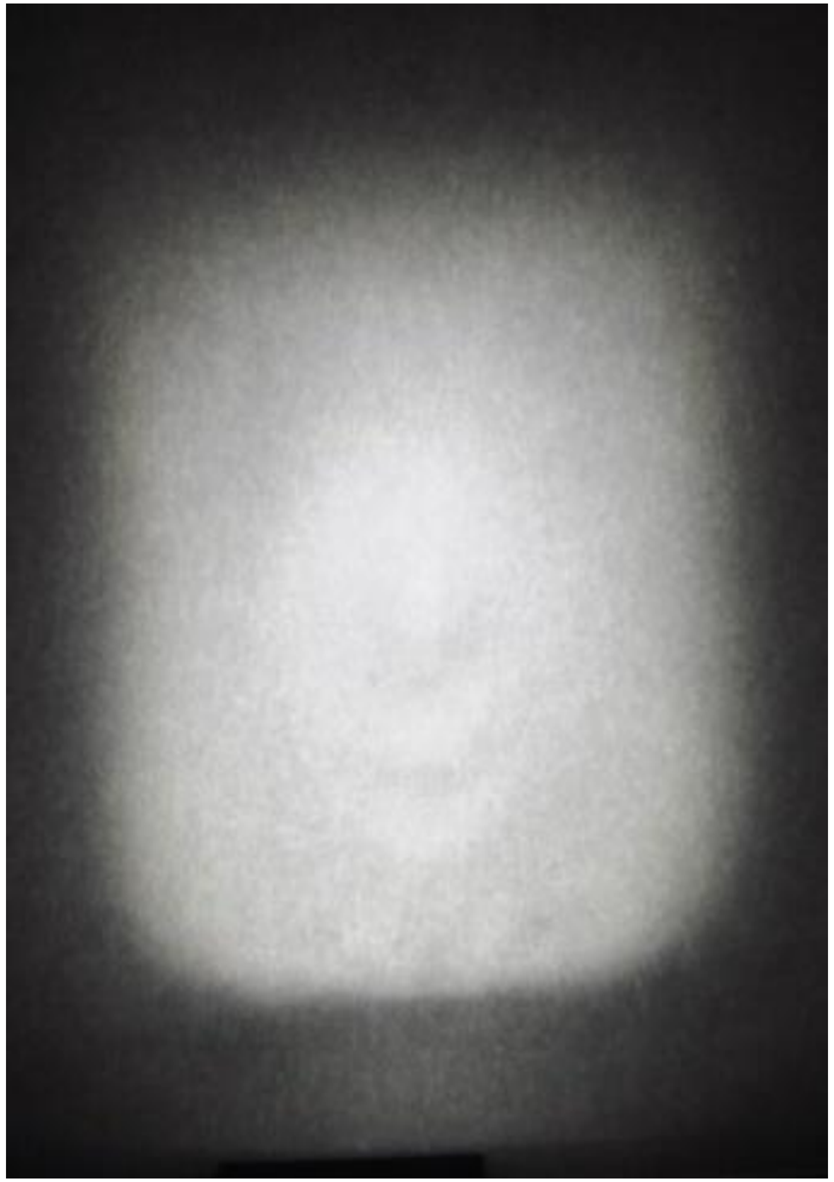
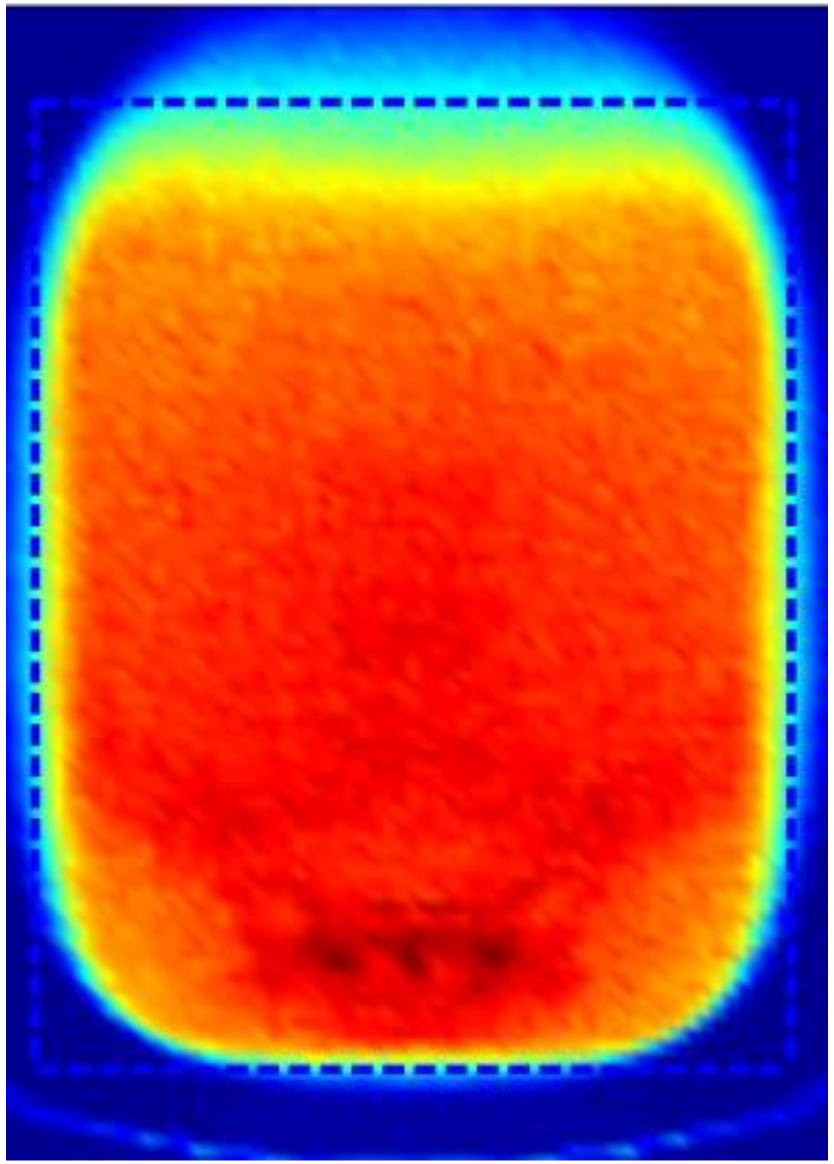
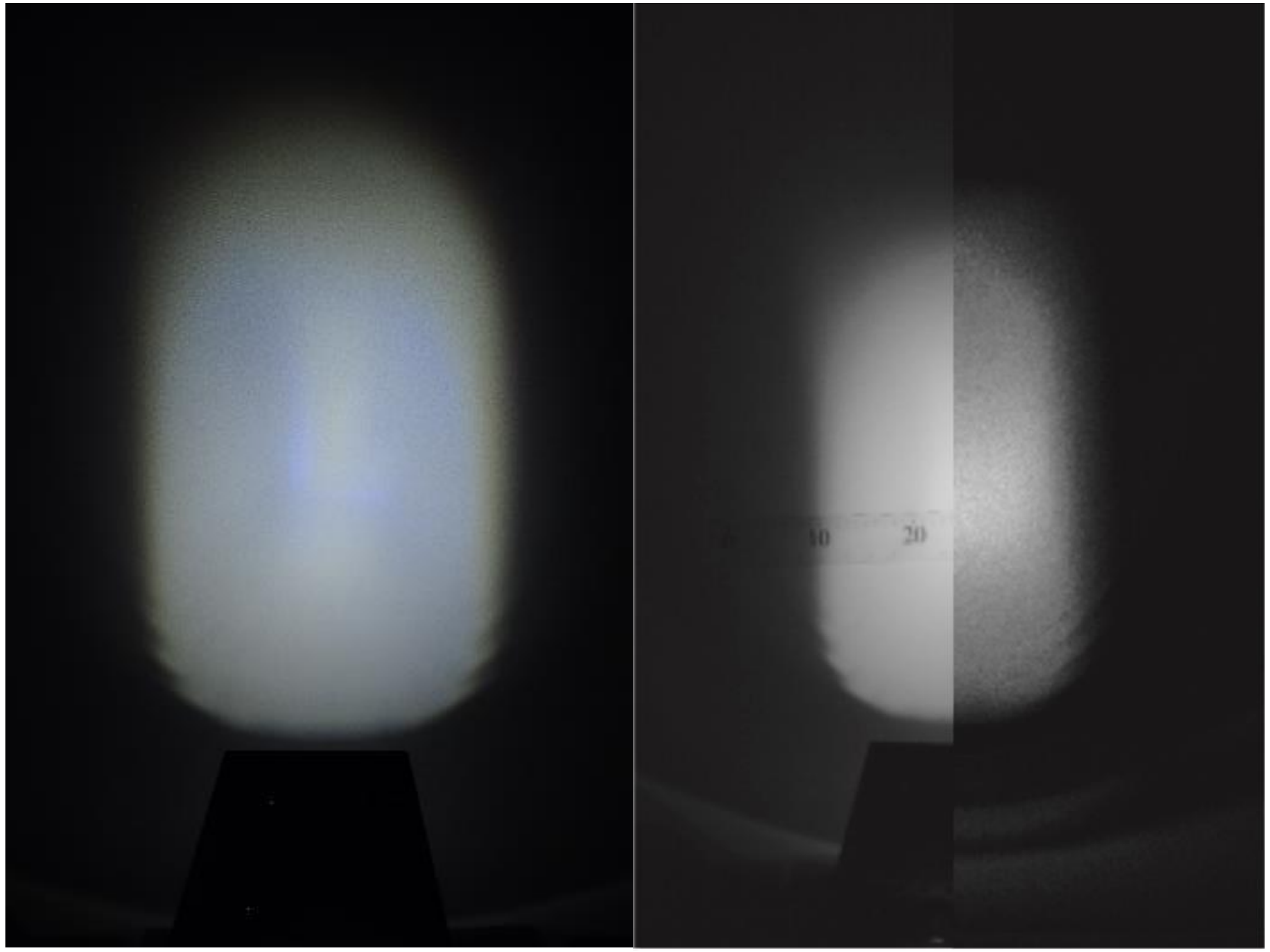








Application Example FF-MOES: Wall-Wash Luminaire



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Conclusion

- FF-MOEs for light management are proving to very promising for the future as they have
  - similar optical functionalities like free-form optics
  - the potential to be mastered and manufactured cost-effectively with alternative approaches
- They can be used in various applications, in this contribution we demonstrated their use in two lighting applications:
- Realizing a wall wash luminaire with FF-MOEs
- Enhancing a linear direct-lit luminaire system by
  - increasing the homogeneity of the illumination of the exit surface from a CV(RSME) value of 0.481 to 0.036,
  - reducing the number of LEDs needed per meter by 56%, while maintaining a good system efficiency of 75.4% compared to 81.4% without optics.

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Thank you for your attention!