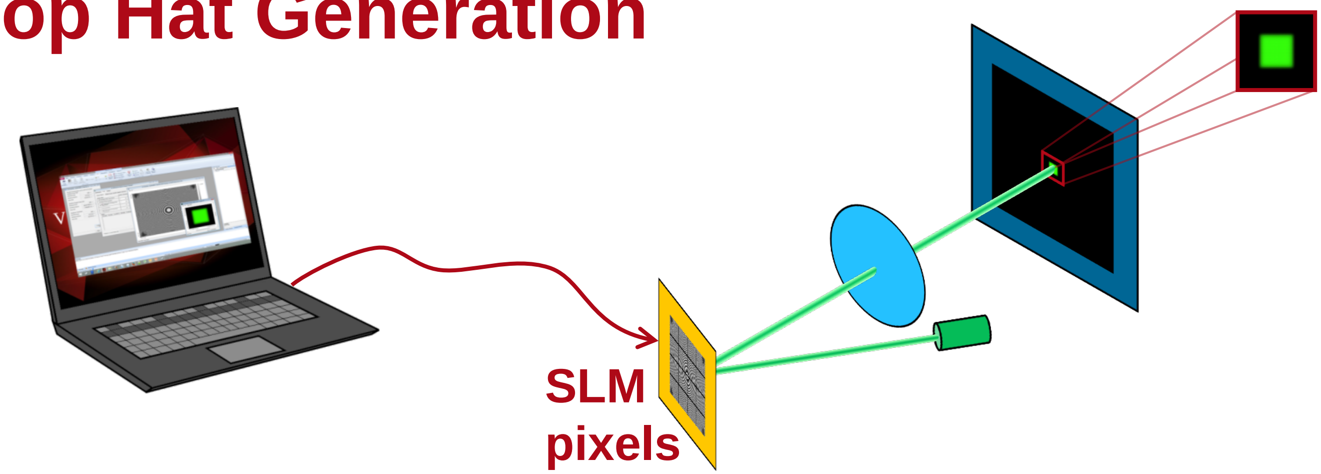
Spatial Light Modulator (SLM.0001 v1.1)

Design of SLM Phase Modulation for Top Hat Generation

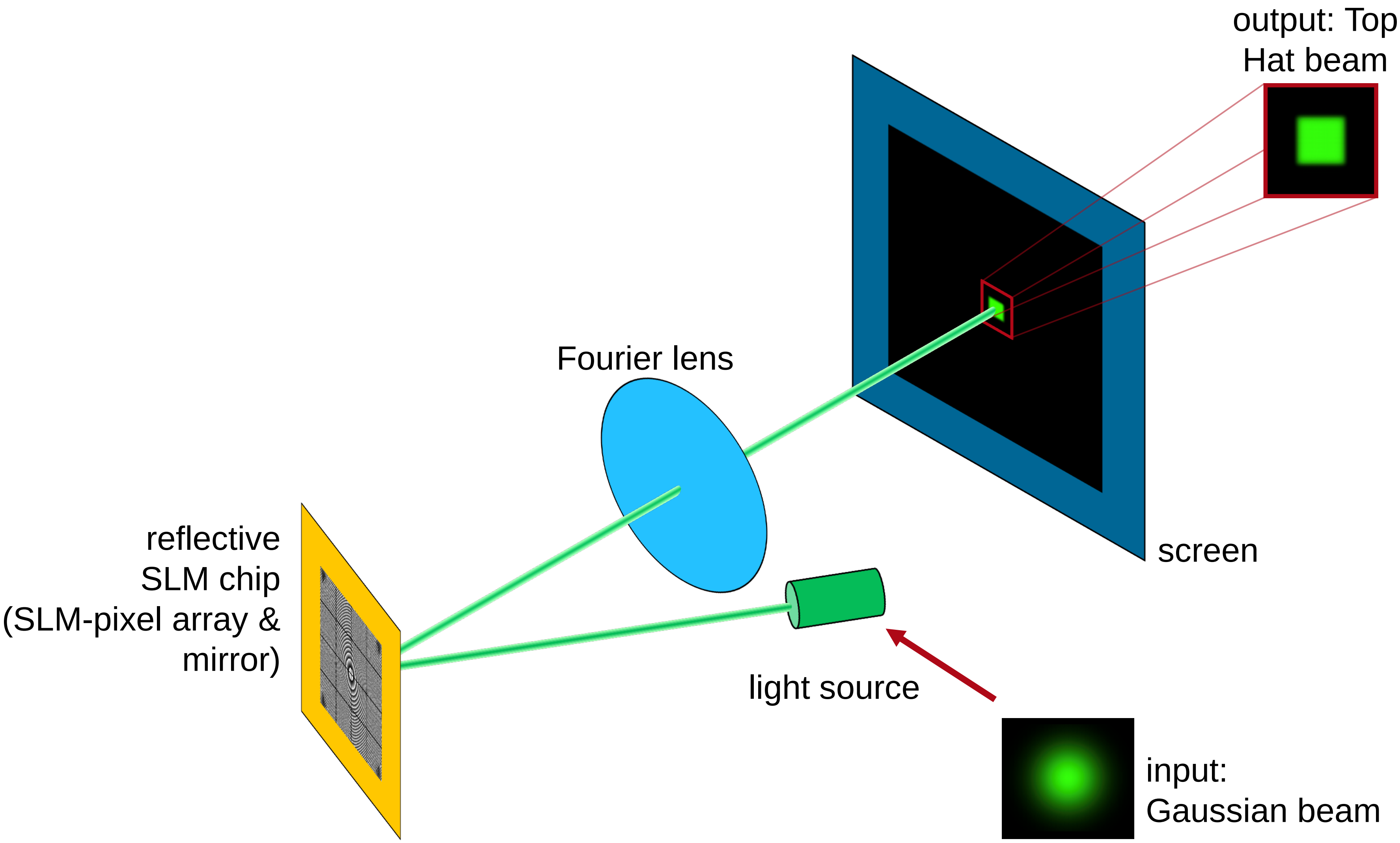


Application Example in a Nutshell

System Details

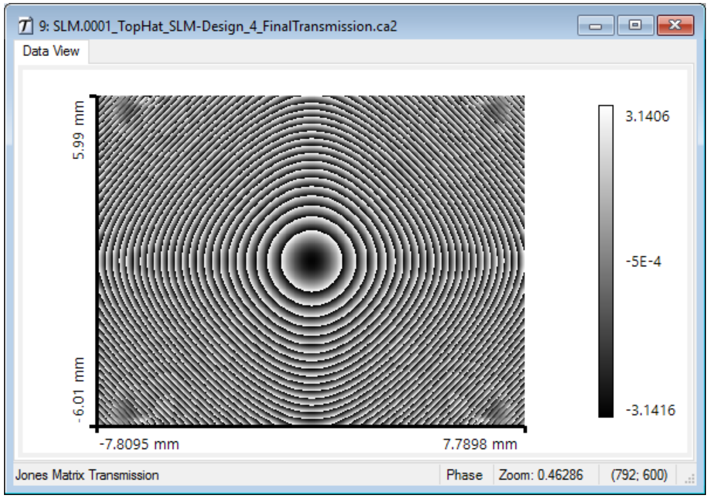
- Source
  - Gaussian laser beam
- Components
  - reflective spatial light modulator (SLM) element with subsequent 2f-setup
- Detectors
  - emulation of visual perception
  - electromagnetic field distribution
  - efficiency, SNR, uniformity error, stray light evaluation
- Modelling/Design
  - ✓ design of phase-only transmission function by **Iterative Fourier Transform Algorithm** (**IFTA**) to shape a **Gaussian beam into a Top Hat**
  - ✓ Field Tracing: **light diffraction at SLM pixel array**

System Illustrations

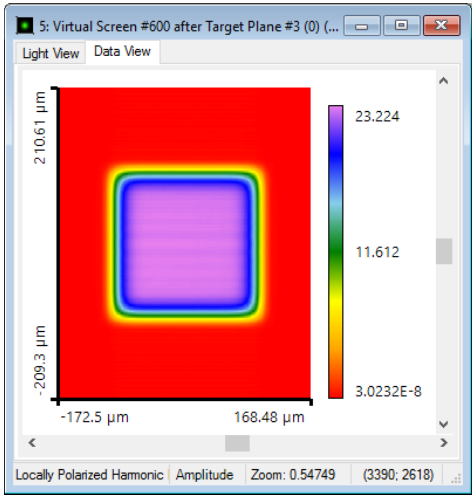


Modeling & Design Results

optimized design of phase distribution



simulated output field in target plane



resulting merit function values

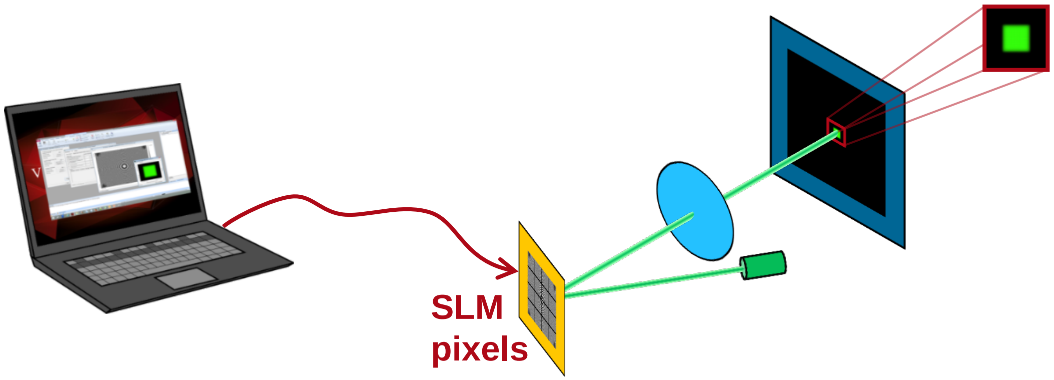
Sub - Detector	Result
Conversion Efficiency (Classic Field Tracing)	99.062 %
Signal-to-Noise Ratio (Classic Field Tracing)	47.644 dB
Uniformity Error (Classic Field Tracing)	5.7575 %
Maximum Relative Intensity of Stray Light (Classic Field Tracing)	1.1193 %

Summary

With the build-in tools of VirtualLab such as

- its **Iterative Fourier Transform Algoritm (IFTA)**,
- an assisting **Session Editor** and
- the **Classic Field Tracing** simulation engine that provides diverse options to deal most suitably with diffractive effects

we have



1. **generated an optimized phase distribution designed for a** reflective spatial light modulator (**SLM**) and
2. **analyzed** the simulated output in its **final setup configuration**.

Application Example in Detail

System Parameters

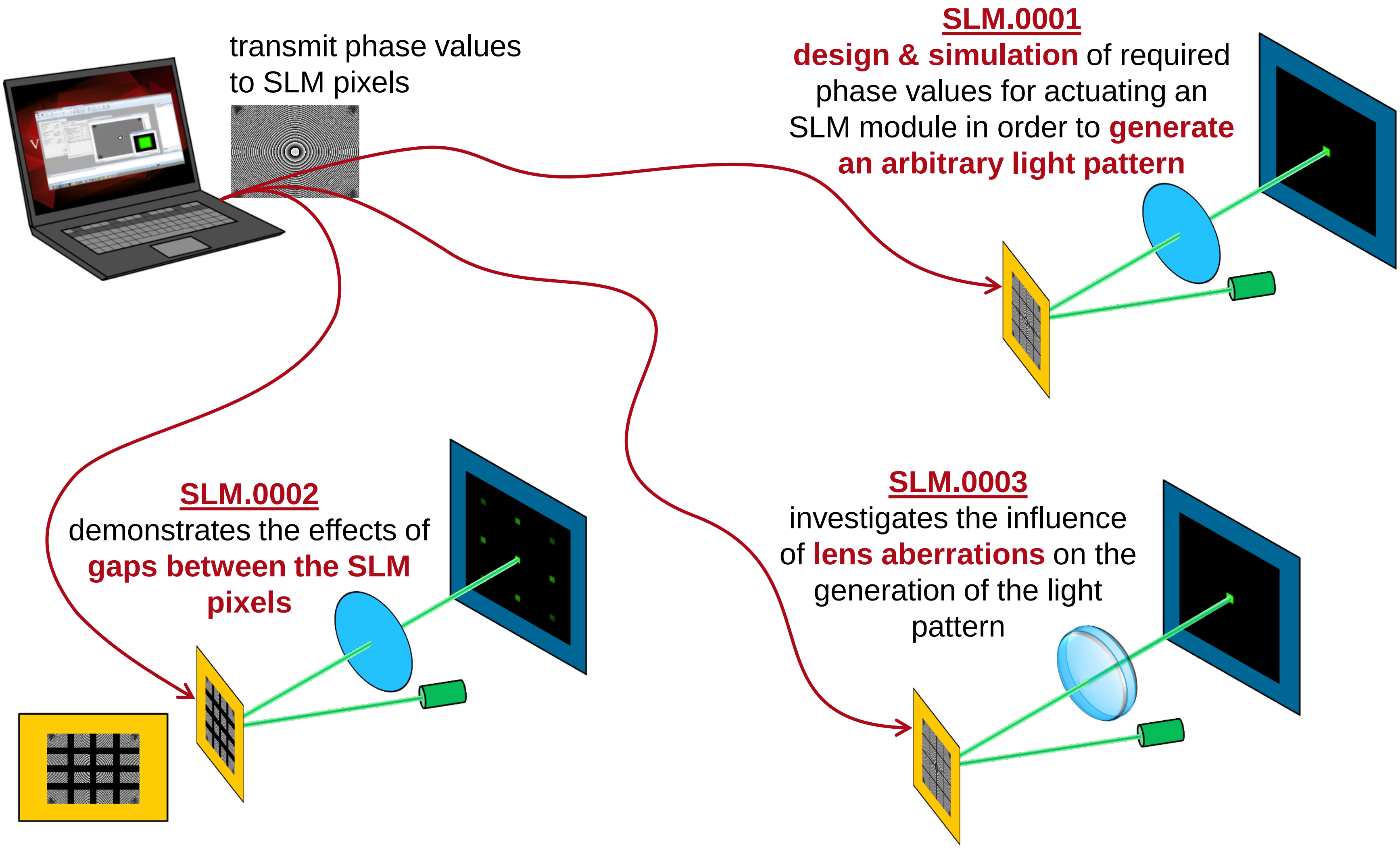
Content Overview

1. First the simulation specifications, the general system and the evaluation results are shown in detail.

2. This is followed by a step-by-step description of how to setup such a simulation yourself.

3. The final part gives you the necessary information what is necessary to export the designed and analyzed data for the actual usage with the SLM module.

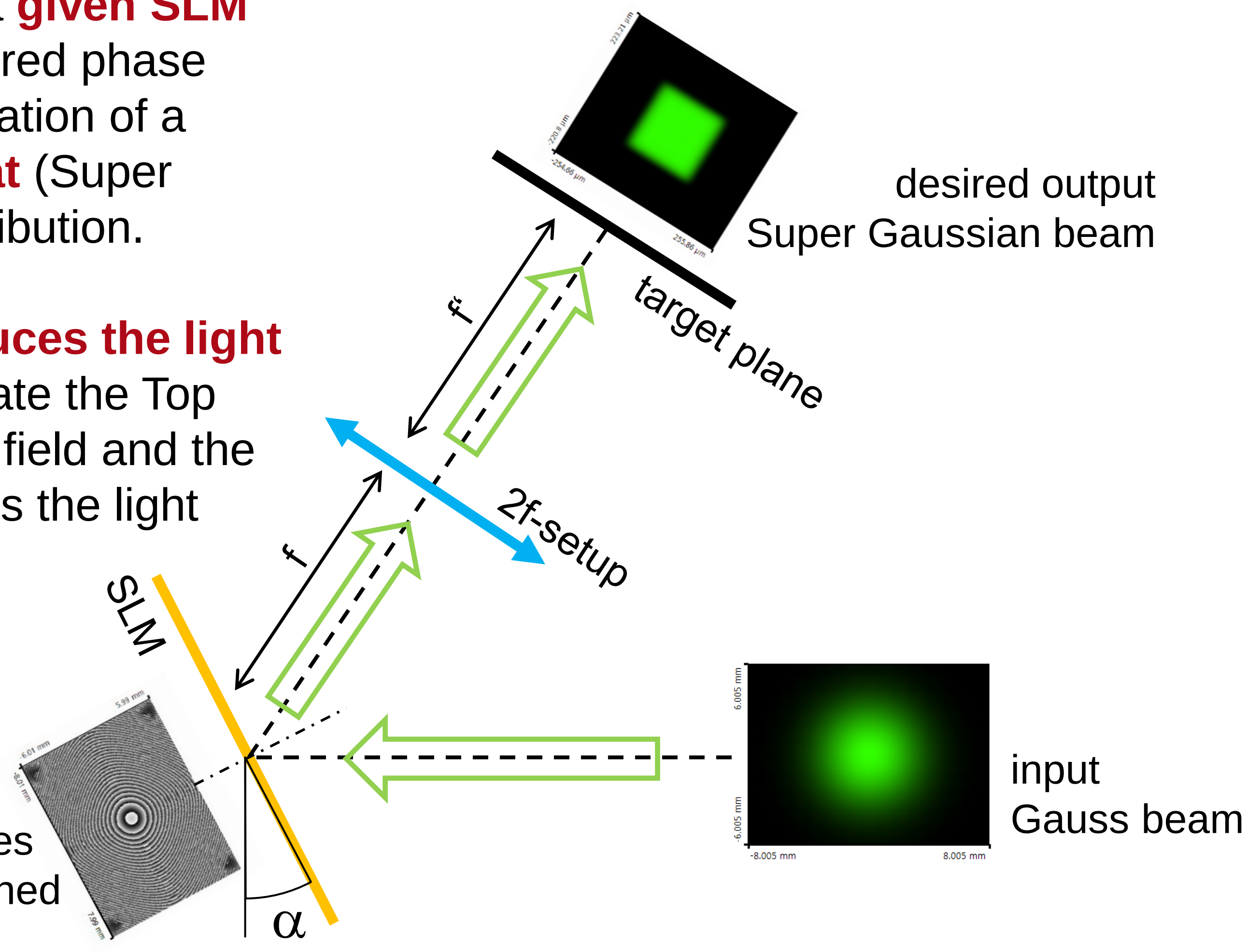
Context of This Application Example



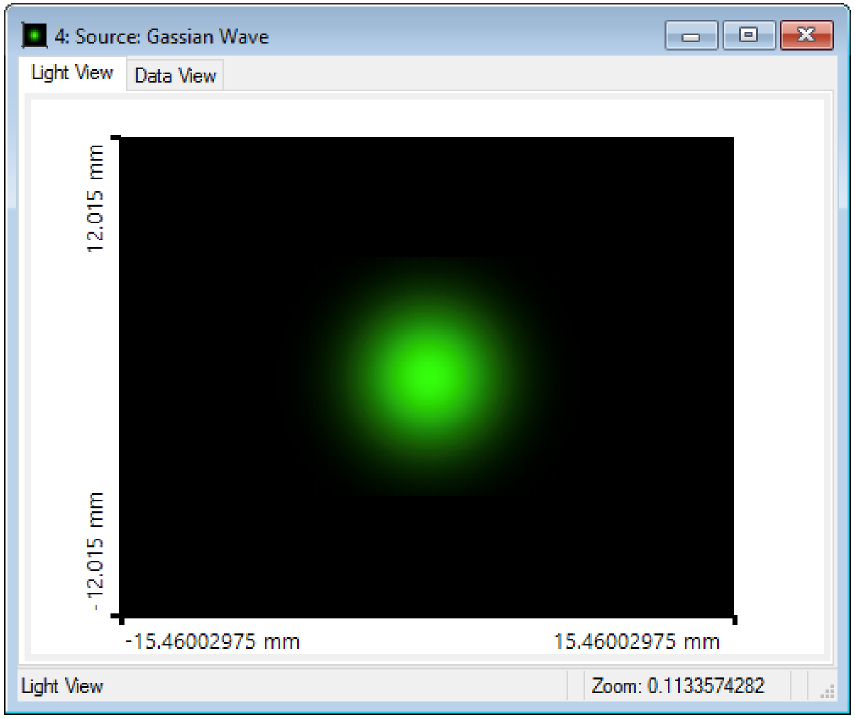
Design & Simulation Task

- For a 2f-setup and a **given SLM** we **design** the required phase values for the generation of a **rectangular Top Hat** (Super Gaussian) light distribution.

- I.e. the **SLM introduces the light deflection** to generate the Top Hat shape in the far field and the **Fourier lens** focuses the light and defines the final working distance.



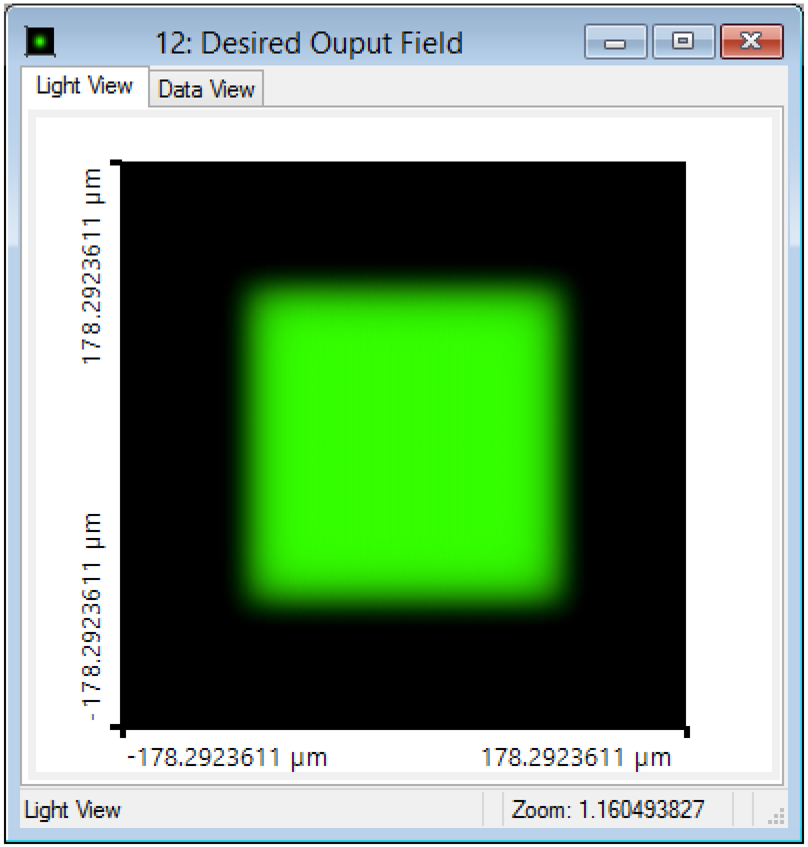
Specs: Input Laser Beam



Single Mode Gaussian Laser

Parameter	Value & Unit
wavelength	532 nm
beam radius ($1/e^2$)	3.3 mm
divergence angle of beam intensity	0.003° x 0.003° (full angle $1/e^2$)
M^2-value	1

Specs: 2f-Setup & Desired Output Beam



Desired Beam Profile in Target Plane

The **2f-setup** corresponds to an ideal lens with

- f = 50 mm
- f‘ = 50 mm

Super Gaussian (Top Hat)

Parameter	Value & Unit
$1/e^2$ radius	100 µm
edge width (measured from 90% to 10% decay of intensity)	26 µm
desired efficiency	> 95%
desired SNR	> 30 dB

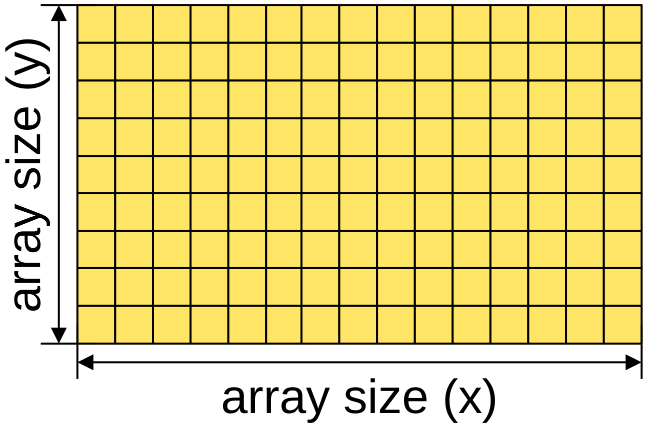
Specs: Design Conditions

- **General DOE vs SLM Design**
  For diffractive optical elements whose structure is put into some substrate material, the pixel size in x and y direction can be chosen quite freely. **For SLM applications these sizes are fixed according to the size of the SLM pixels**.

- **Reflective Setup**
  In case of a reflective SLM setup, where the SLM is tilted, the incident light “sees” only the area of tilted SLM-pixels. Thus **the pixel size of the transmission function has to be adapted** for the design as the design and optimization algorithm assumes perpendicular incident light.

Specs: SLM Pixel Array = Transmission

SLM pixel array top view:



For the design the **gaps** between the SLM pixels **are not regarded.**

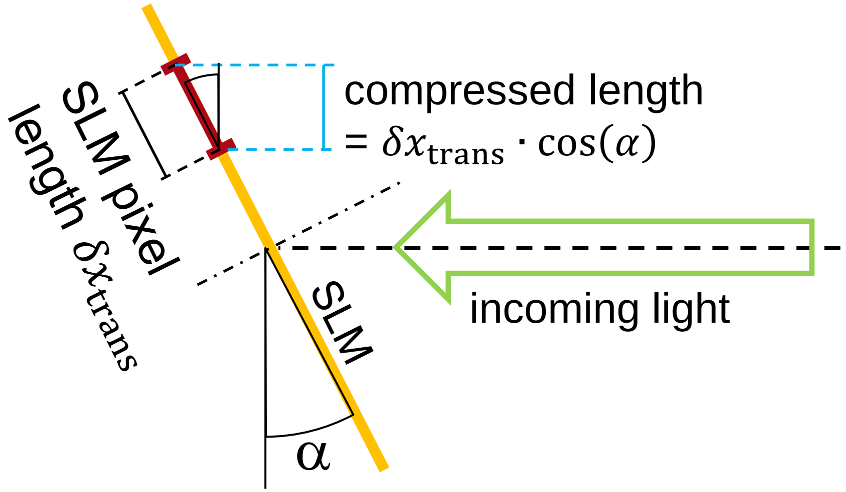
I.e. here, in **SLM.0001** we assume an **area fill factor of 100%**.

Hamamatsu X10468	**Value & Unit**
array size X x Y	792 x 600 pixels
pixel pitch X x Y	20 µm x 20 µm
area size X x Y	15.84 mm x 12 mm
area fill factor	100% (*)
element tilt α with respect to optical axis	10° about the Y axis

*(*) Actually the Hamamatsu X10468 has an area fill factor of **98%**. The corresponding effect is the topic of **SLM.0002**.*

Compressed Length Regards for Design

- Due to the **reflective setup** with a tilt angle about the Y axis, the **incident light „sees“** the SLM‘s X lengths in **a compressed view**, perpendicularly regarded.

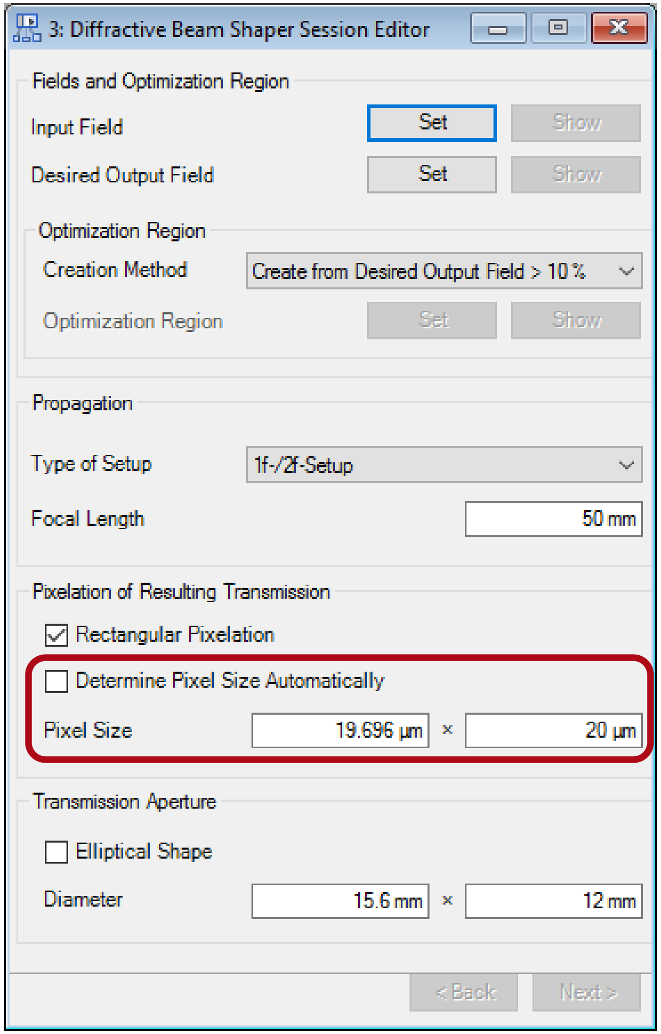


- For the design – using the iterative Fourier transform algorithm (IFTA) with normal incident consideration – this is accommodated for by multiplying the X lengths of the SLM and its pixels, respectively, with the factor cos(α):

compressed SLM pixel length = $20\,\mu\text{m} \cdot \cos(10°) = 19.696\,\mu\text{m}$

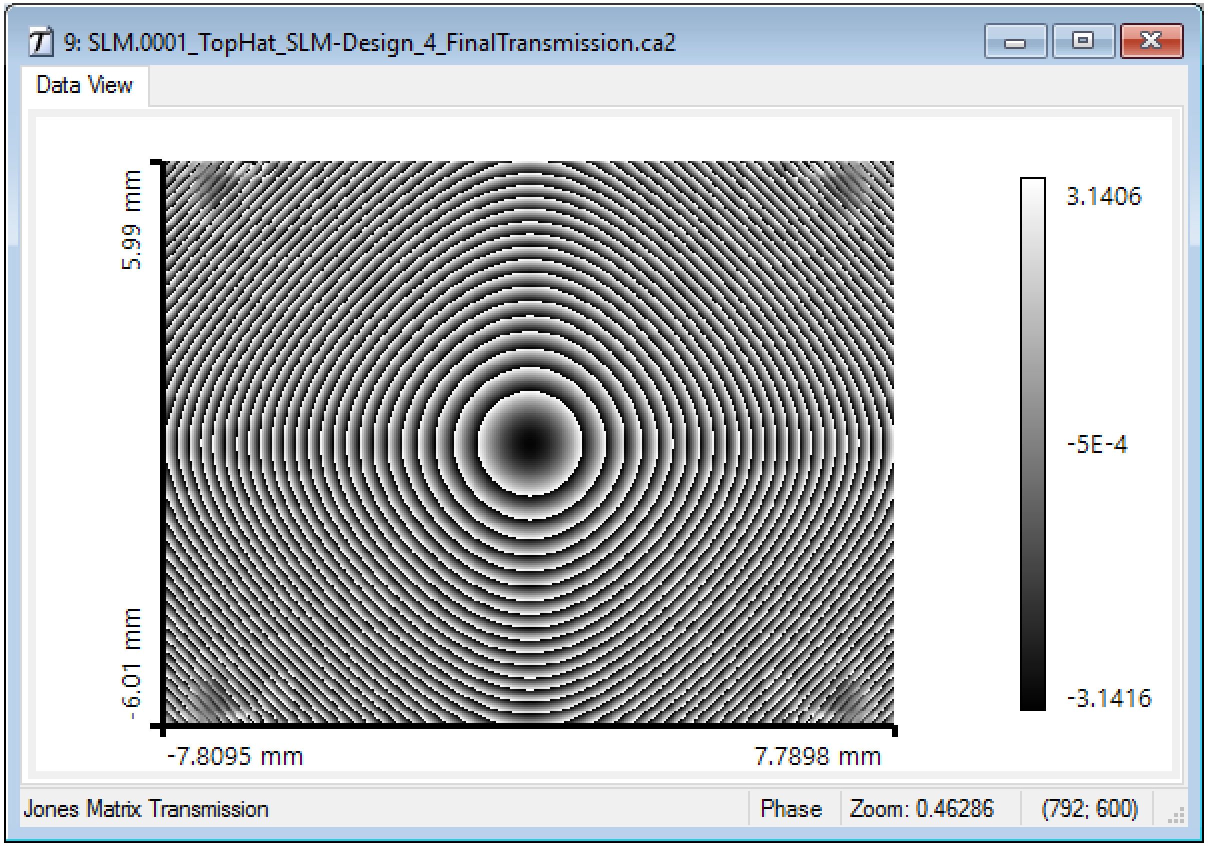
compressed total SLM length = $15.84\,\text{mm} \cdot \cos(10°) = 15.600\,\text{mm}$

Assistance for Design & Optimization



- VirtualLab provides a so-called **Session Editor** for beam shaping which assists you while configuring the design and optimizing the document.
- Mostly, it is used for the design of a classic **diffractive optical element** (DOE) whose **pixel size is variable** and will be determined during the design process.
- For an SLM-setup the element‘s **pixel size is a fixed parameter** and therefore **has to be specified manually** in the Session Editor.

Design Results: Phase Transmission Function

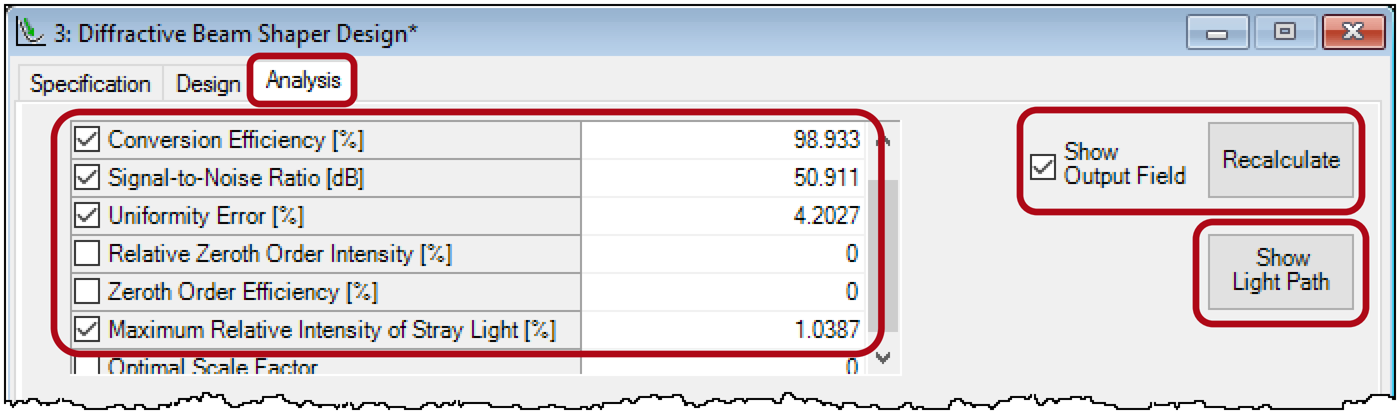


Adjacent the resulting phase distribution is shown in 2π modulo display.

Application Example in Detail

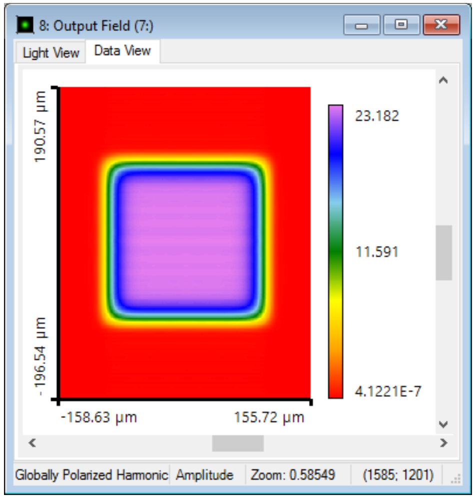
Simulations & Results

Design Results: Merit Functions & Output



- The **characteristic parameters** of the resulting design can be calculated on the Analysis tab. The **output field** (amplitude) is shown in false (rainbow) colors.

- Clicking *Show Light Path* opens the system's Light Path Document (LPD).

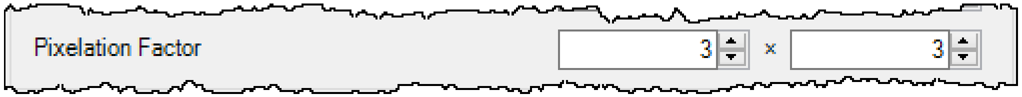


Settings before Simulating in Tilted Setup 1-2

The designed phase data is already inserted into the opened LPD, automatically. For a **reflective SLM setup some adjustments** have to be made:

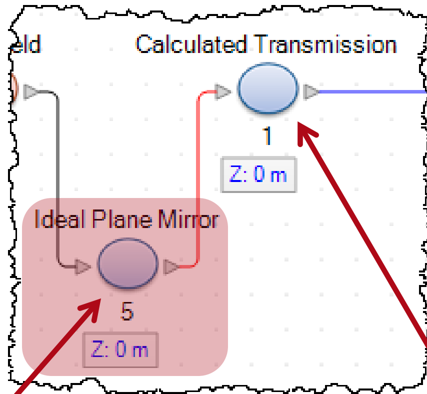
1. The **sampling distance** of the designed transmission has to be set back according to the **actual SLM parameters** (20 µm x 20 µm) as the tilted optical element of course has its original pixel size.

2. Furthermore, VirtualLab allows for consideration of optical effects caused by the **rectangular pixel shape**.

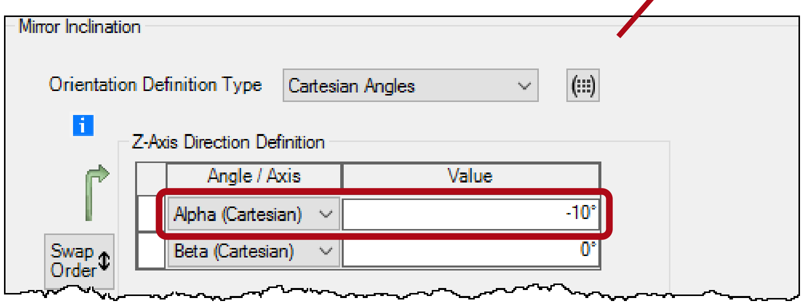


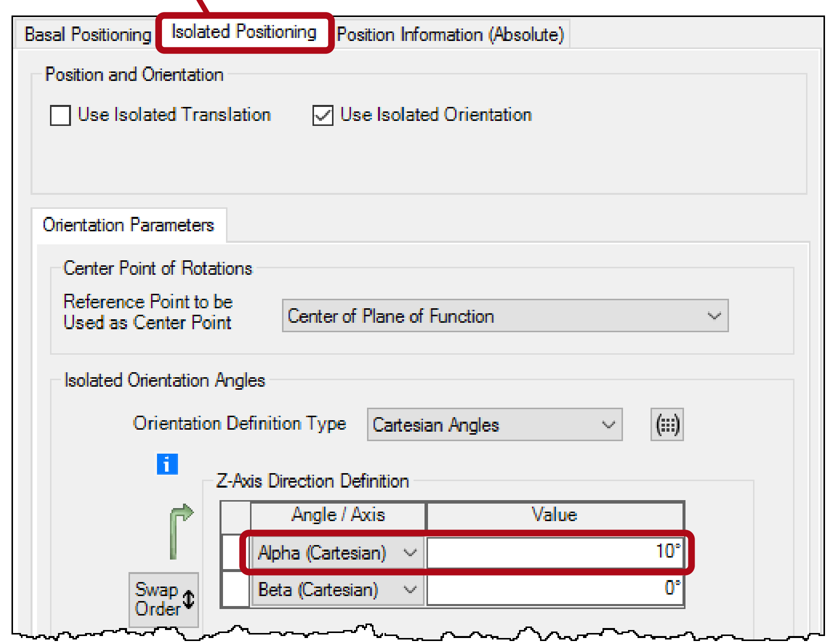
Settings before Simulating in Tilted Setup 3-4

3. Afterwards, the tilted reflecting setup needs to be configured by adding an **ideal mirror.**

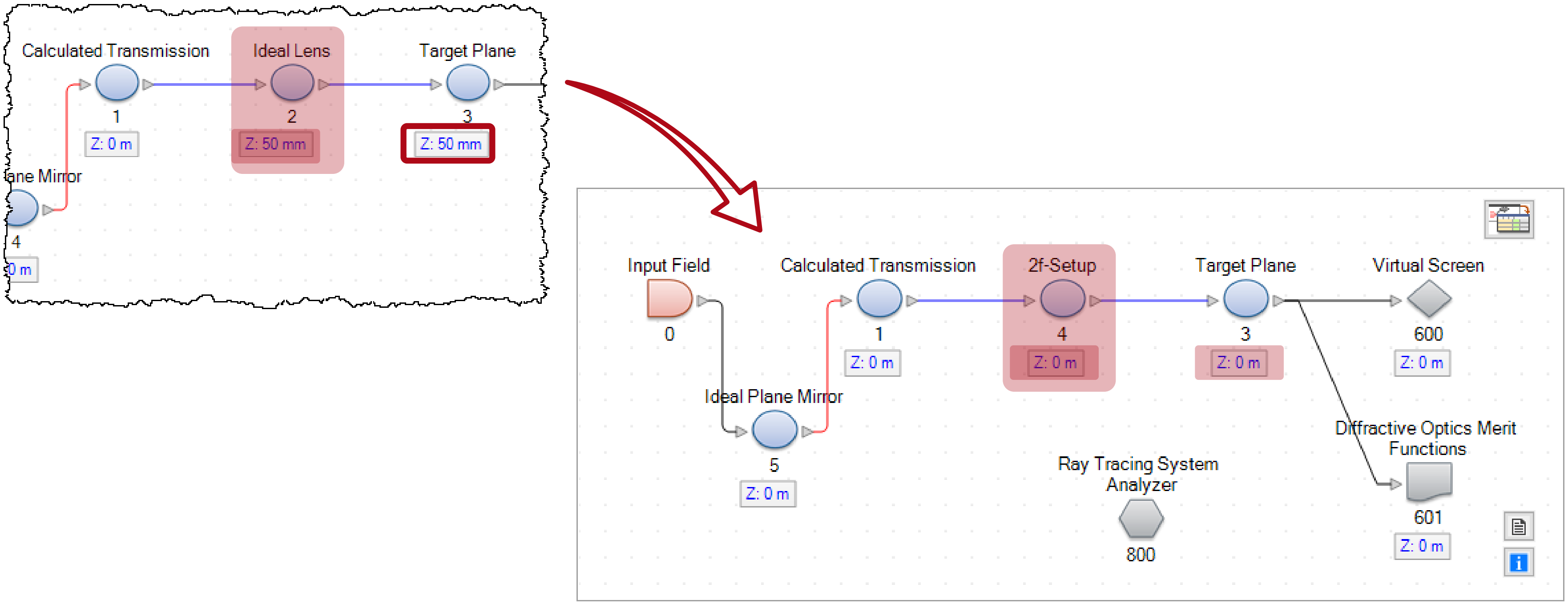


4. Then, the necessary tilt angles in both elements are to be set.



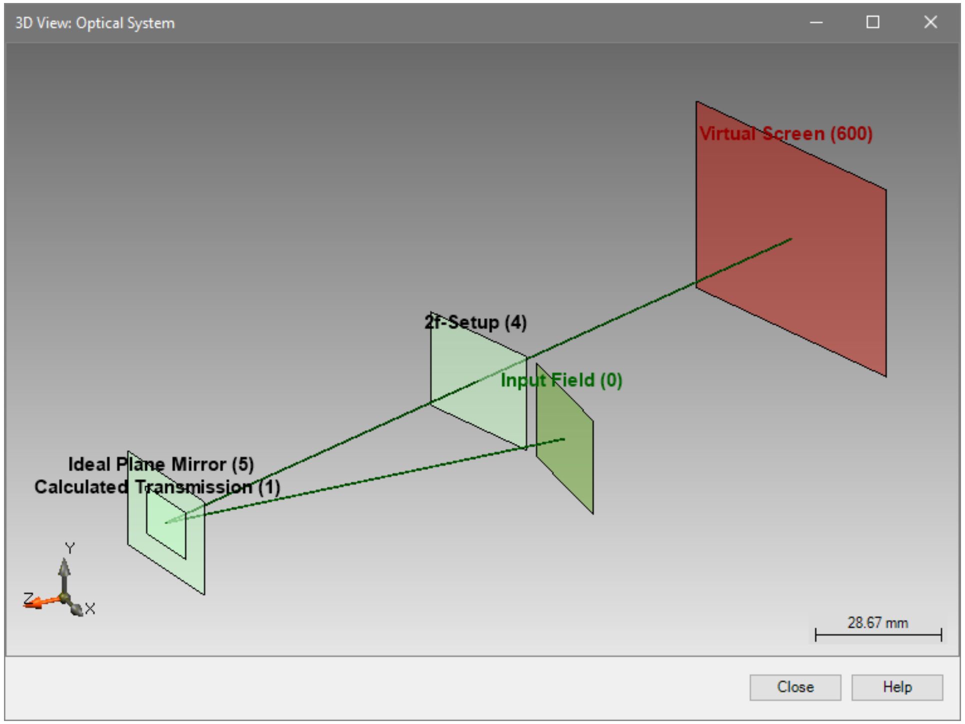


Settings before Simulating in Tilted Setup 5



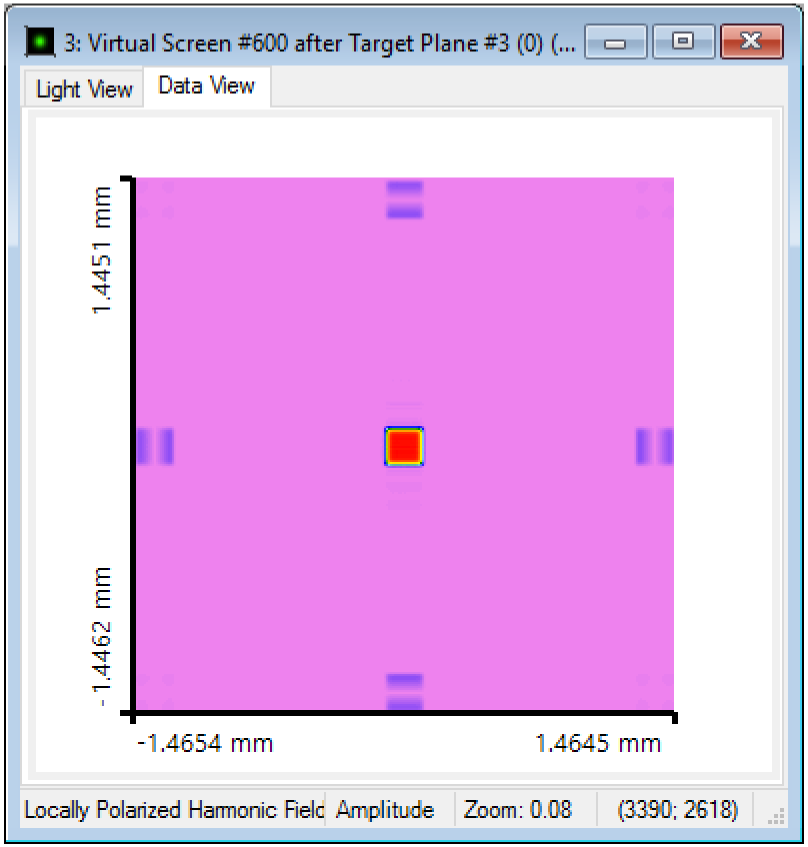
5. Because the ***Ideal Lens*** element is not suited for off-axis non-paraxial simulations, it has to be exchanged by
   - either the later intended lens (see SLM.0003) in order to consider the associated aberrations
   - or – as is demonstrated here – by a ***2f-Setup*** element, which realizes a perfect aberration free Fourier lens.

System‘s 3D Display



For **illustrational purpose** an additional distance was introduced between the different elements to demonstrate the setup configuration. This is not necessary for the simulation. (The *2f-Setup* element considers already the propagation distance in front and behind.)

Higher Sinc Order Evaluations



- The simulation of each SLM pixel by several data points allowed the regard of the **diffraction effects caused by the periodic structure**.
- The resulting diffraction orders are modulated by a *sinc* function (so-called **higher sinc orders**), due to the rectangular structure of each pixel.
- This intensity modulation affects the achievable uniformity error. During the IFTA design process it is possible to compensate this effect.

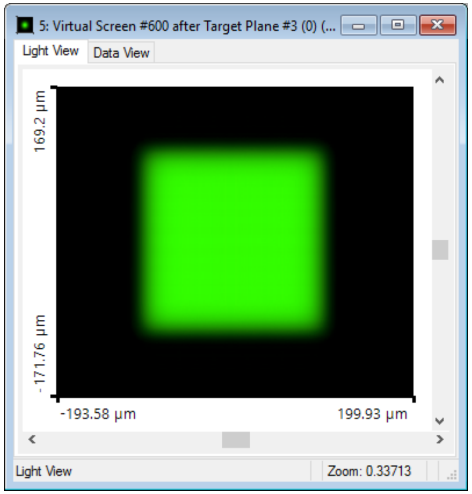
System's Simulation Results

The result of system simulation exhibits that the desired **requirements**

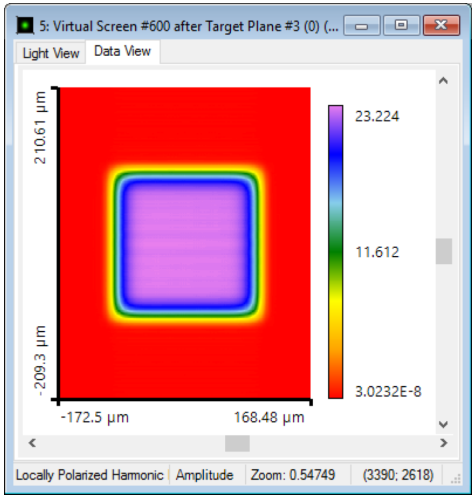
- efficiency > 95%
- SNR > 30 dB

are easily met.

Visual Perception



Amplitude in False Colors



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With the build-in tools of VirtualLab such as

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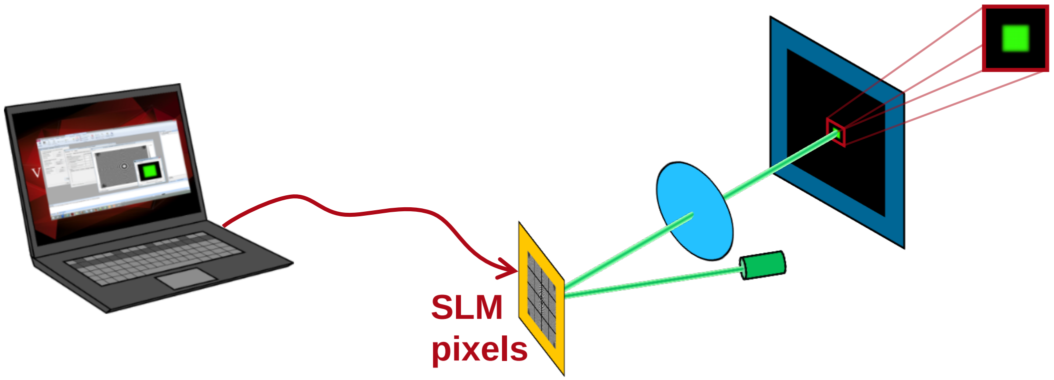


1. **generated an optimized phase distribution designed for a** reflective spatial light modulator (**SLM**) and
2. **analyzed** the simulated output in its **final setup configuration**.

Step by Step Instructions

General approach for setting pp an SLM system and performing the design, including optimization & analysis

Skip

Design & Analysis Procedure

DESIGN

1. Check the basic conditions according to the utilized SLM module.
2. Specify input and desired output field.
3. In case of non-normal incidence, calculate the according size of the compressed appearing SLM pixels.
4. Define the whole setup by configuring the diffractive beam shaping session editor for assisted transmission design & optimization.
5. Do a geometric pre-design followed by the final iterative design & optimization.

ANALYSIS

1. Generate the Light Path Diagram and configure the aperture size and final sampling size of the SLM.
2. Convert the Light Path Diagram, insert an ideal plane mirror element. Then adjust the orientation of this mirror and the transmission element.
3. Exchange the ideal lens by the intended 1f/2f-setup element, adjust the distances and select the diffractive rotation operator for all affected propagations.
4. Set a pixelation factor in the transmission element for diffraction regard due to the rectangular SLM pixels.
5. Perform the simulation.

D1: Given Facts – Due to SLM Geometry

- Due to the fixed size of the SLM-pixels the maximum extension of the resulting **output field is predetermined**. The adjacent formula calculates this extension.
- These **constrictions are considered automatically** by the settings of the diffractive beam shaping session editor of VirtualLab.
- The total size of the SLM is fixed either. Thus the **achievable target field resolution follows directly** and can be calculated by the second adjacent formula.

Diameter of the output field D_{out} (for 1f/2f-setups with $\Delta z = f$):

$$D_{\text{out}} = 2\Delta z \cdot \tan\left(\arcsin\left(\frac{\lambda}{2\delta x_{\text{trans}} n_{\text{out}}}\right)\right)$$

paraxial & $n_{\text{out}} = 1$ → $D_{\text{out}} = \frac{\Delta z \lambda}{\delta x_{\text{trans}}}$

Sampling distance of the output field δx_{out}:

$$\delta x_{\text{out}} = \Delta z \cdot \tan\left(\arcsin\left(\frac{\lambda}{D_{\text{trans}} n_{\text{out}}}\right)\right)$$

paraxial & $n_{\text{out}} = 1$ → $\delta x_{\text{out}} = \frac{\Delta z \lambda}{D_{\text{trans}}}$

λ…wavelength; δx_{trans}…SLM pixel size; D_{trans}…size of designed transmission (in case of a beam shaping application = SLM diameter); n_{out}… refractive index of outer material

D1: Achievable Output Field Parameters

The given SLM allows

- a total **output field size** of

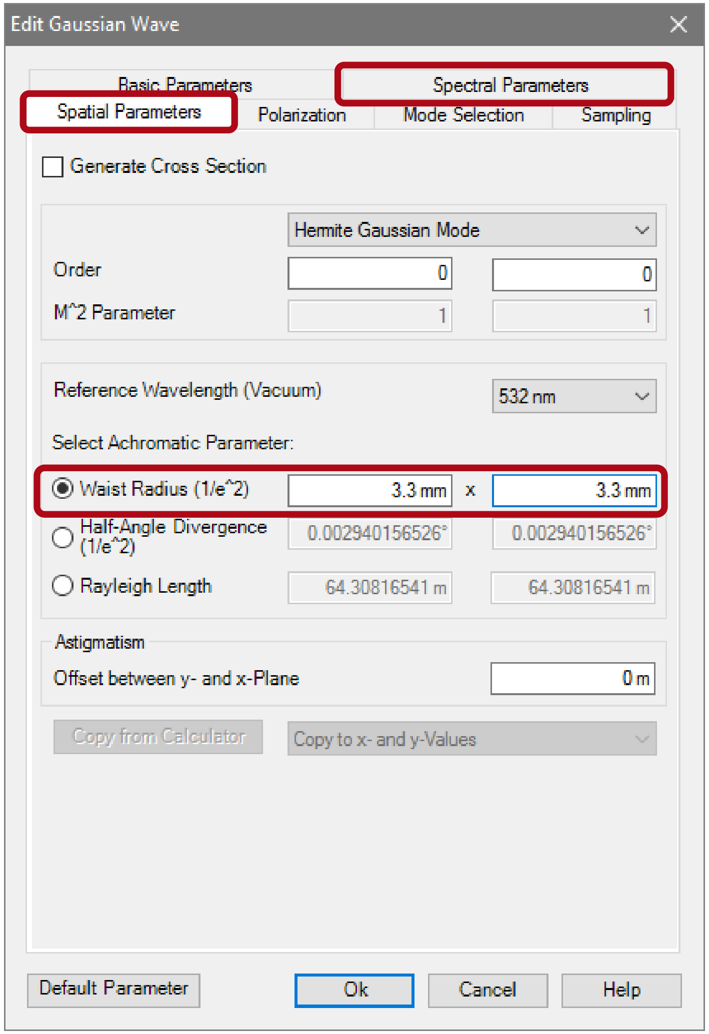
$$D_{\mathrm{out}} = \frac{\Delta z \lambda}{\delta x_{\mathrm{trans}}} = \frac{50\,\mathrm{mm} \cdot 532\,\mathrm{nm}}{20\,\mu\mathrm{m}} \approx 1.33\,\mathrm{mm}$$

- and an **achievable resolution in the target plane** in *x* and *y* direction of

$$\delta x_{\mathrm{out},x} = \frac{\Delta z \lambda}{D_{\mathrm{trans}}} = \frac{50\,\mathrm{mm} \cdot 532\,\mathrm{nm}}{15.84\,\mathrm{mm}} \approx 1.68\,\mu\mathrm{m}$$

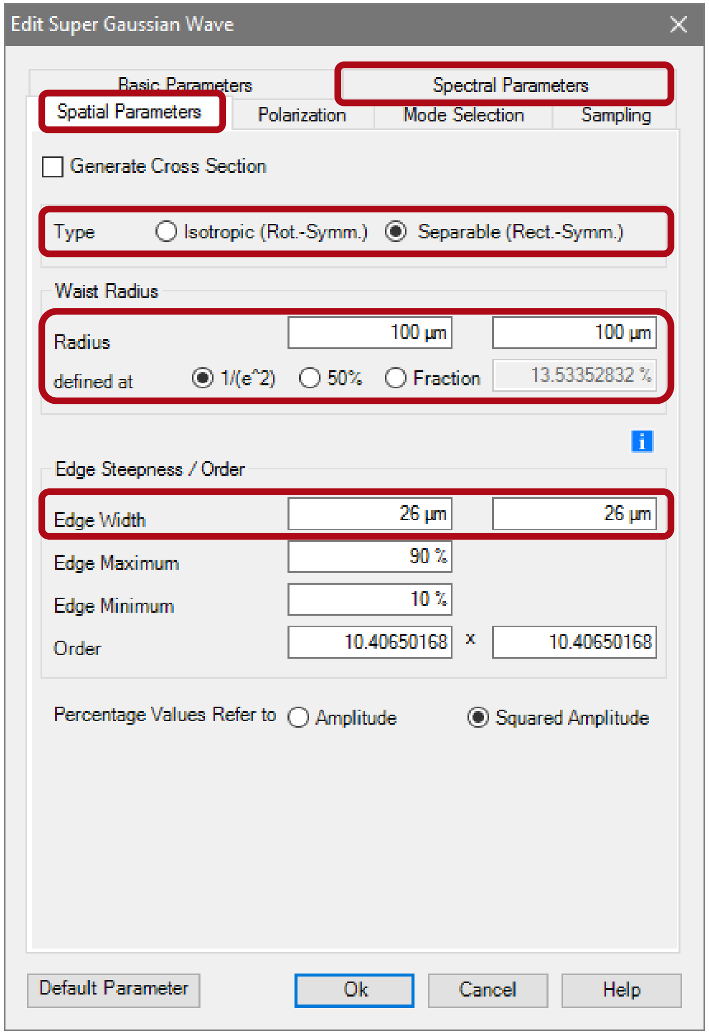
$$\delta x_{\mathrm{out},y} = \frac{\Delta z \lambda}{D_{\mathrm{trans}}} = \frac{50\,\mathrm{mm} \cdot 532\,\mathrm{nm}}{12\,\mathrm{mm}} \approx 2.22\,\mu\mathrm{m}.$$

D2: Input Field



- For the generation of the input field VirtualLab's source models can be used.
- For the intended incident laser beam light distribution we use the Gaussian Wave model from the Sources ribbon
  - on Spectral Parameters tab specify the wavelength
  - on Spatial Parameters tab specify the $1/e^2$ waist radius

D2: Output Field



- For the generation of the output field VirtualLab's source models can be used.
- For the definition of the desired target light field distribution we use the Super-Gaussian Wave model from the Sources ribbon
  - On „Spectral Parameters“ tab specify the wavelength
  - On Spatial Parameters tab specify
    - Separable (Rect.-Symm.)
    - $1/e^2$ waist radius
    - edge width (should be larger than the single target spot radius resulting by the optical setup without the beam shaping element)

D3: Incident Angle

- parameters of the utilized **Hamamatsu SLM X10468:**
  - pixel size in x & y-direction: $\delta x_{\mathrm{trans}} = 20\,\mu\mathrm{m}$
  - full diameter in x & y-direction: $\left(D_{\mathrm{trans},x}; D_{\mathrm{trans},y}\right) = (15.84; 12.00)\,\mathrm{mm}$

- calculate the compressed SLM pixels as they appear if one looks at the SLM at the intended incident Cartesian angle of $\alpha = 10°$:

$$\delta x_{\mathrm{trans,design}} = \delta x_{\mathrm{trans}} \cdot \cos(\alpha) = 20\,\mu\mathrm{m} \cdot \cos(10°) = 19.696\,\mu\mathrm{m}$$

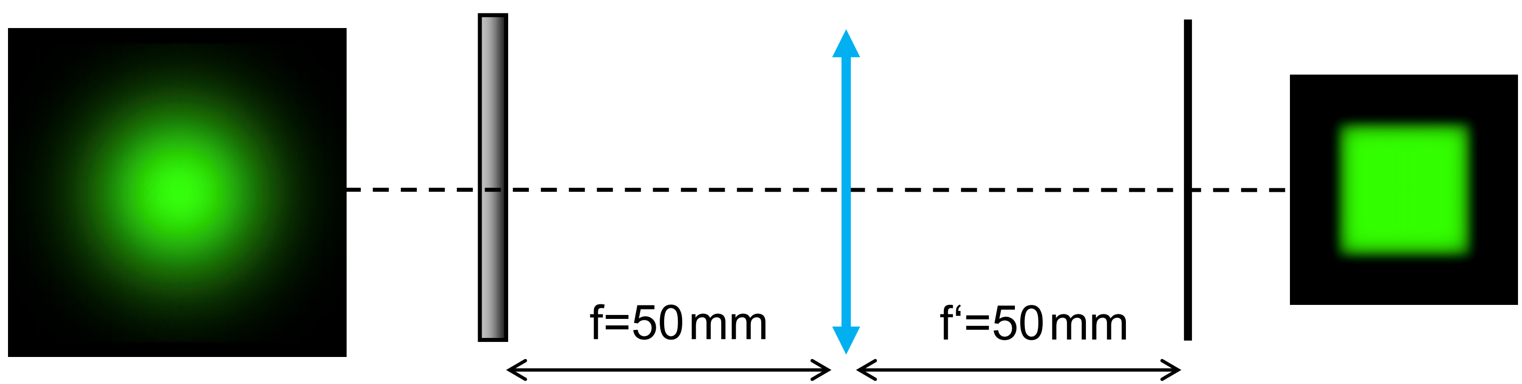
$$D_{\mathrm{trans,design}} = D_{\mathrm{trans}} \cdot \cos(\alpha) = 15.84\,\mathrm{mm} \cdot \cos(10°) = 15.600\,\mathrm{mm}$$

These adapted sizes should be used for the design!

Overview of Setup for IFTA Design Process

transmissive beam shaper
represented by phase-only transmission function
with compressed pixels in x-direction according to tilt angle

target plane



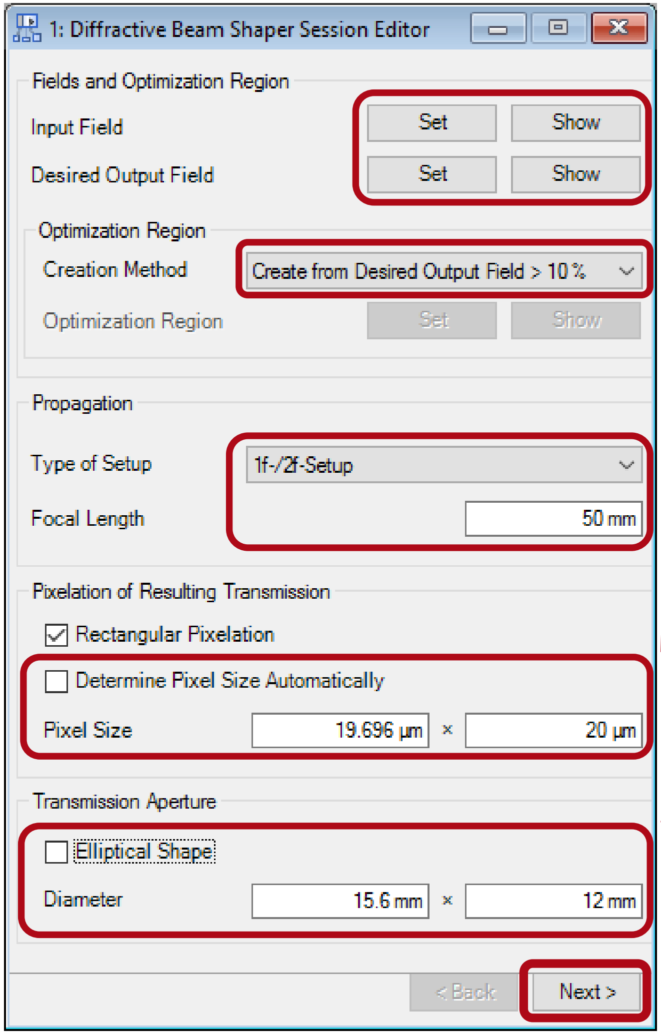
illuminating beam intensity

2f-setup

Top Hat intensity (free of speckles)

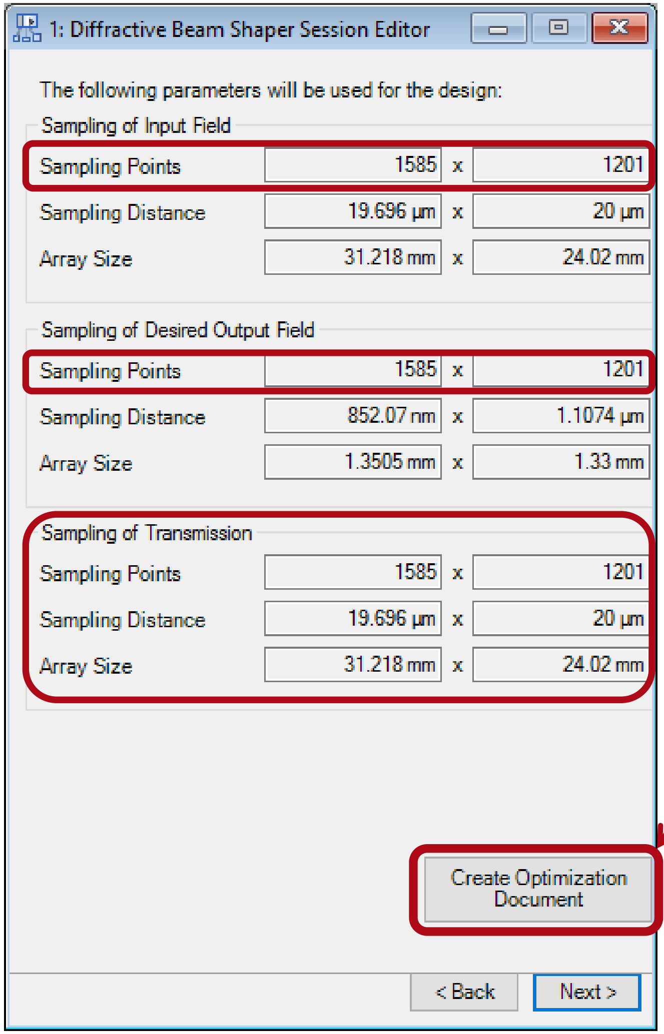
surrounding medium: vacuum

D4: Configuring the Session Editor



- set the created illuminating and target light distribution.
- choose an option for the optimization region
- set the focal length
- specify a fixed pixel size according to the SLM parameters and associated adaptions
- specify the effective SLM aperture size
  (The session editor will increase this aperture size automatically just for the optimization process for a more accurate design.)
- then click *Next* →

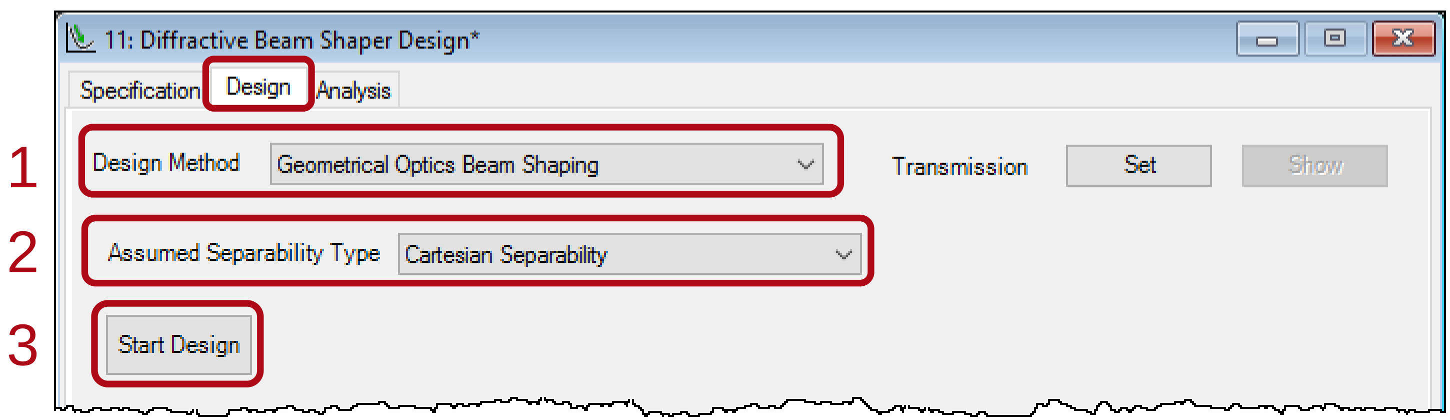
D4: Check via Parameter Overview



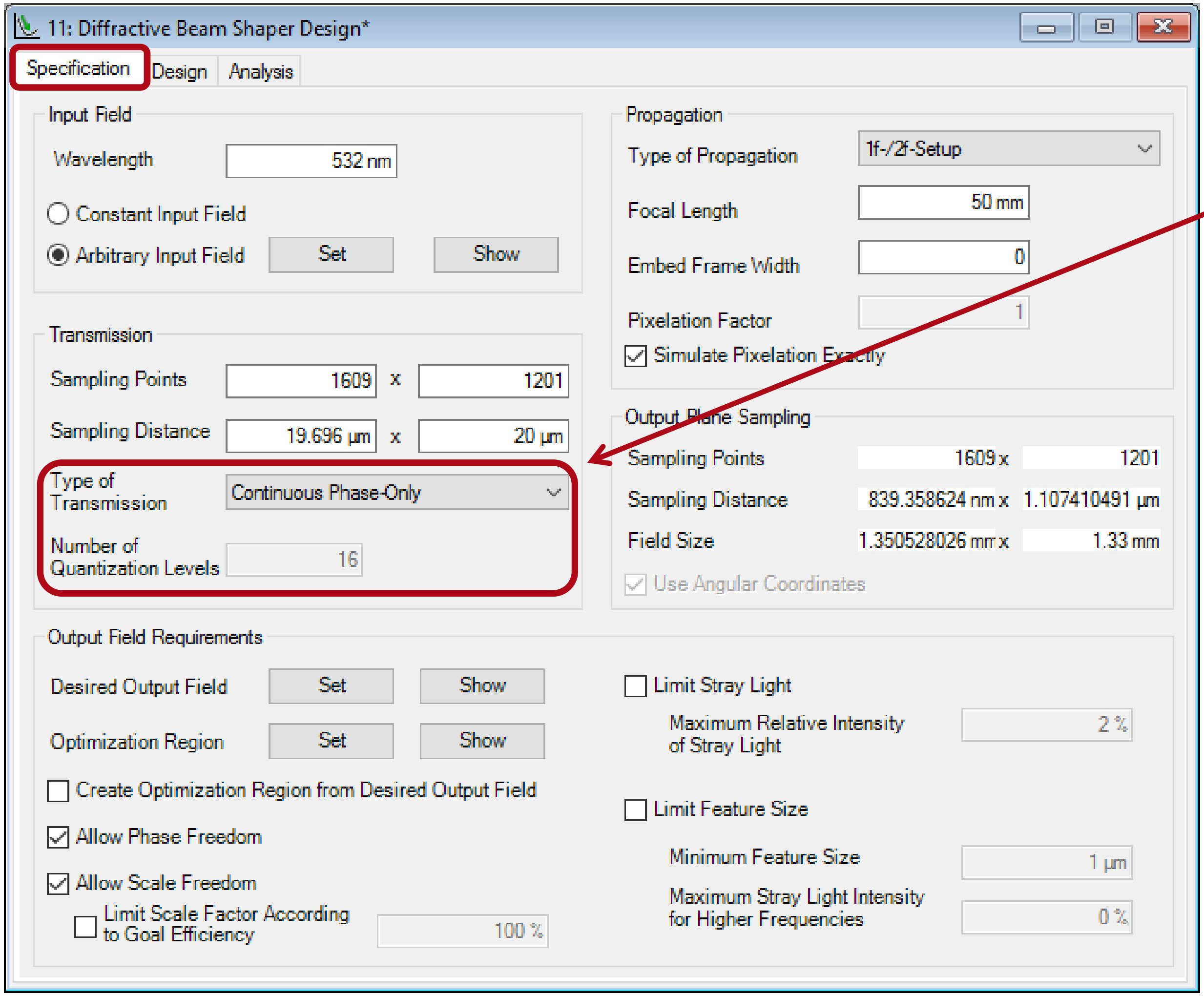
- The aperture size is increase automatically during the optimization process for a more accurate design. Later the correct aperture size will be re-adjusted again.
- Click *Create Optimization Document*.

D5: Geometric Pre-Design

1. For a good starting point for the Iterative Fourier Transform Algorithm (IFTA) a pre-design based on geometrical optics beam shaping is performed.
2. Choose *Cartesian Separability* in case of a rectangular target pattern.
3. Start this initial design.



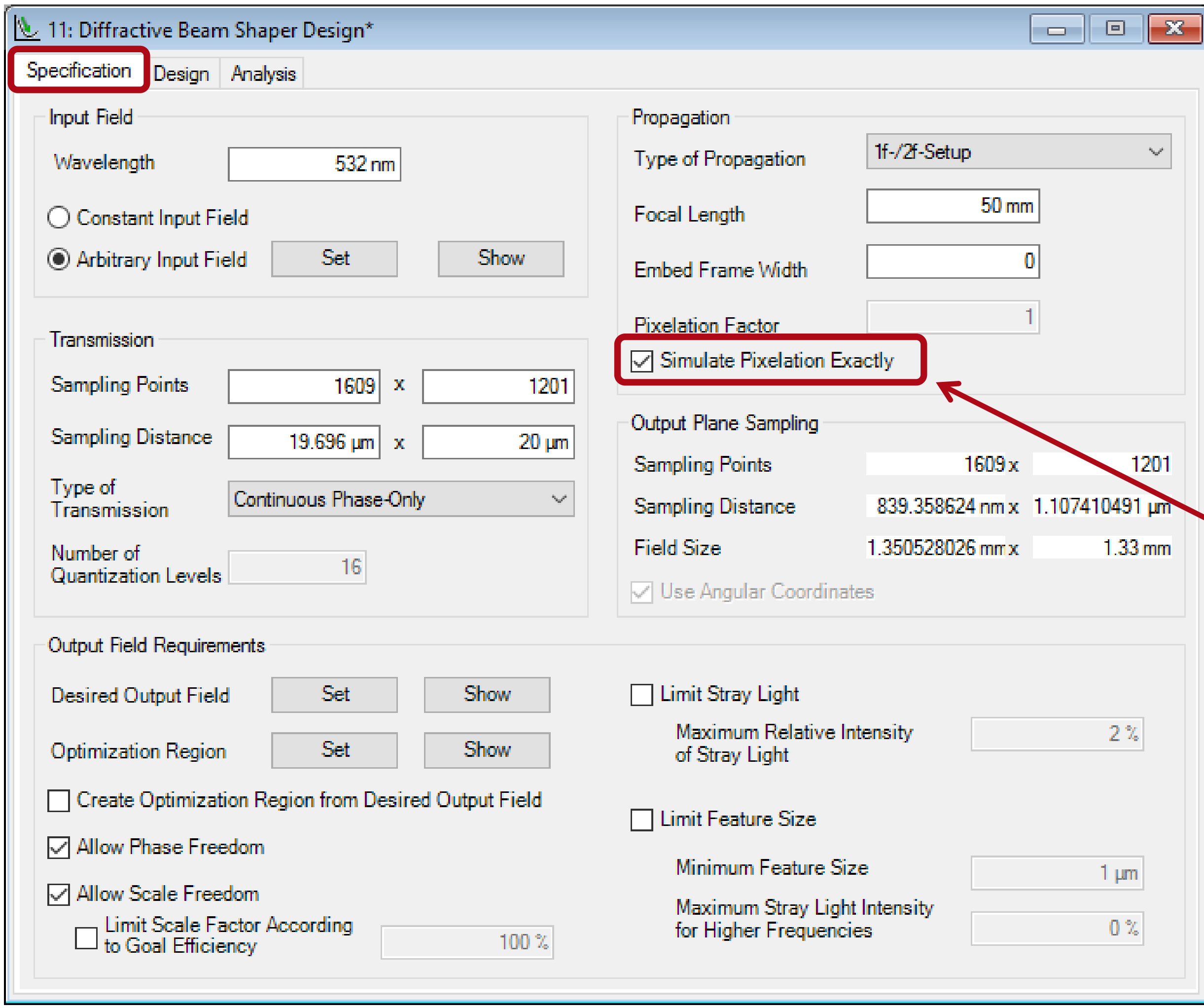
D5: IFTA – Number of Phase Levels



In case your SLM allows only few usable phase levels, you should set the corresponding number on the *Specification* tab after selecting the transmission type „Quantized Phase-Only“.

This Hamamatsu SLM provides practically 8 bit for the phase level representation. Thus it is almost continuous. For the final data export the actual numbers are regarded later.

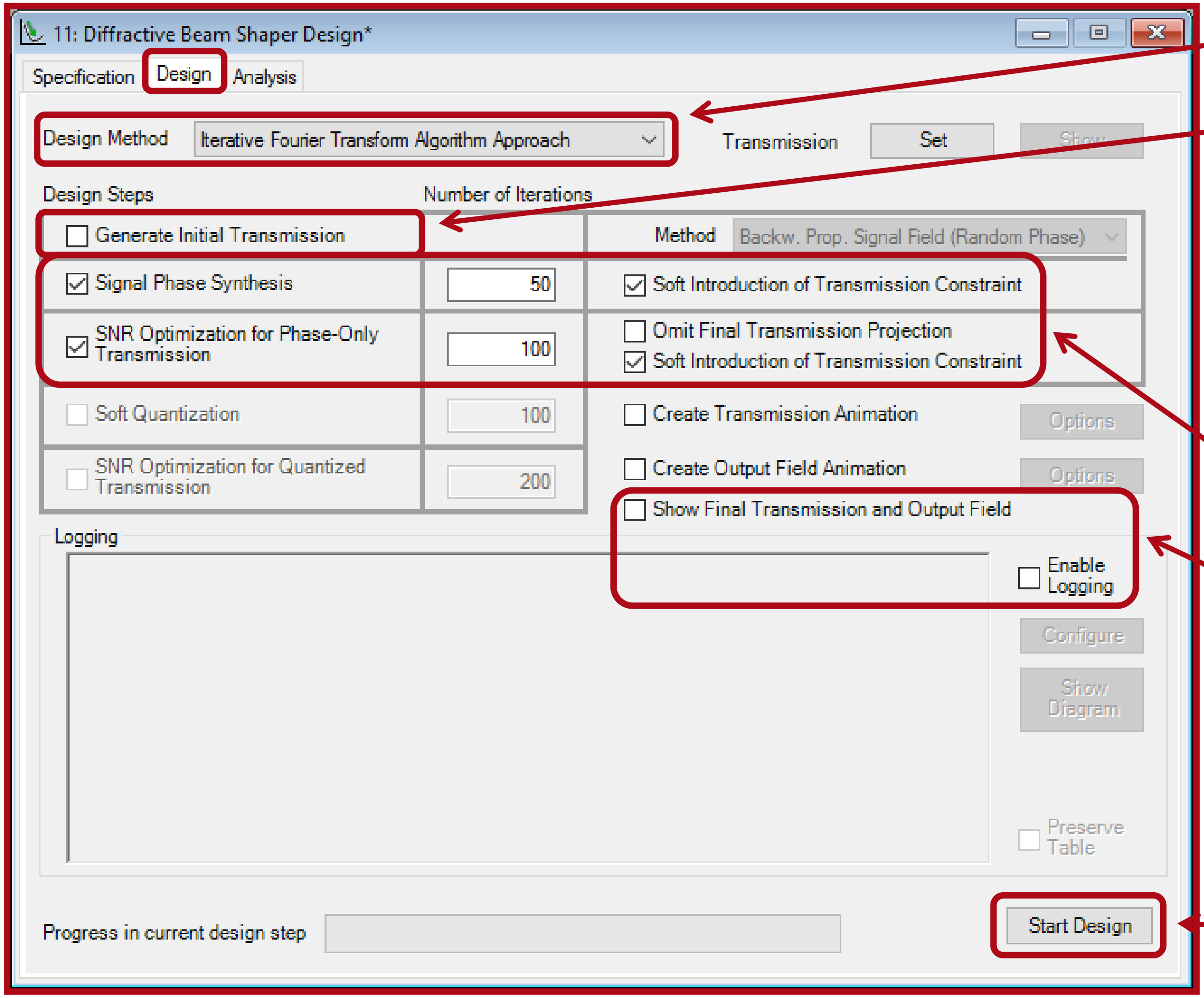
D5: IFTA – Compensate Sinc Modulation



Due to **rectangular pixels** the generated intensity distribution will exhibit a **modulation according to a broad Sinc function**.

By checking the option ***Simulate Pixelation Exactly*** VirtualLab analytically calculates this effect and **compensates** it **during the design**.

D5: IFTA – Design Settings



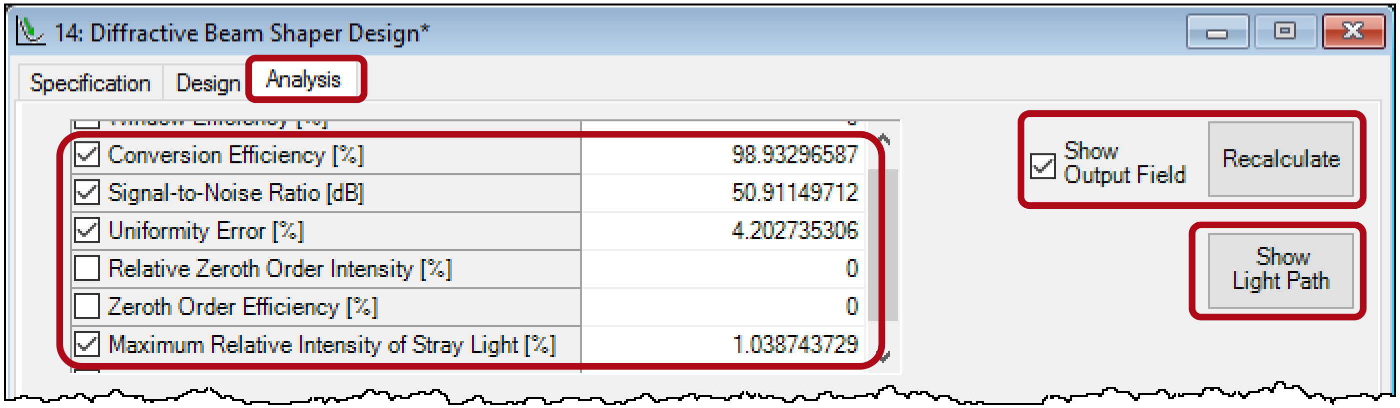
Change to IFTA Approach and deactivate *Generate Initial Transmission* in order to use the previously calculated one as initial transmission.

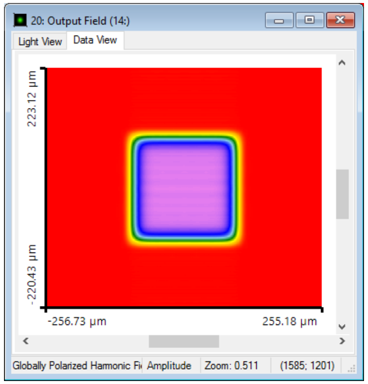
Adjust the design steps.

Deactivate *Show Final Transmission and Output Field* as well as *Enable Logging* in order to reduce the computation time.

Start Design.

IFTA – Pre-Analysis

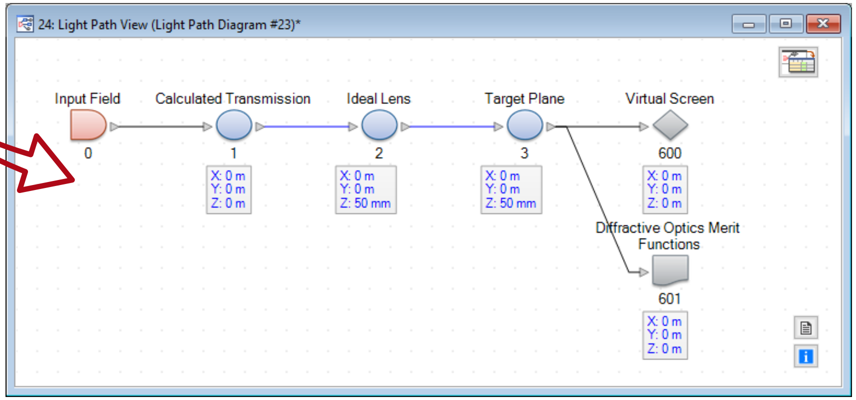




- After the finished design process, review the results on the *Analysis* tab.
- the output field can be displayed e.g. in false (rainbow) colors.
- Because the IFTA uses larger fields during the design of a beam shaper in order to control the phase values appropriately (and thus also higher sampling), the IFTA‘s analysis results will vary slightly from a later simulation of the whole system.

A1: Get Full System – LPD

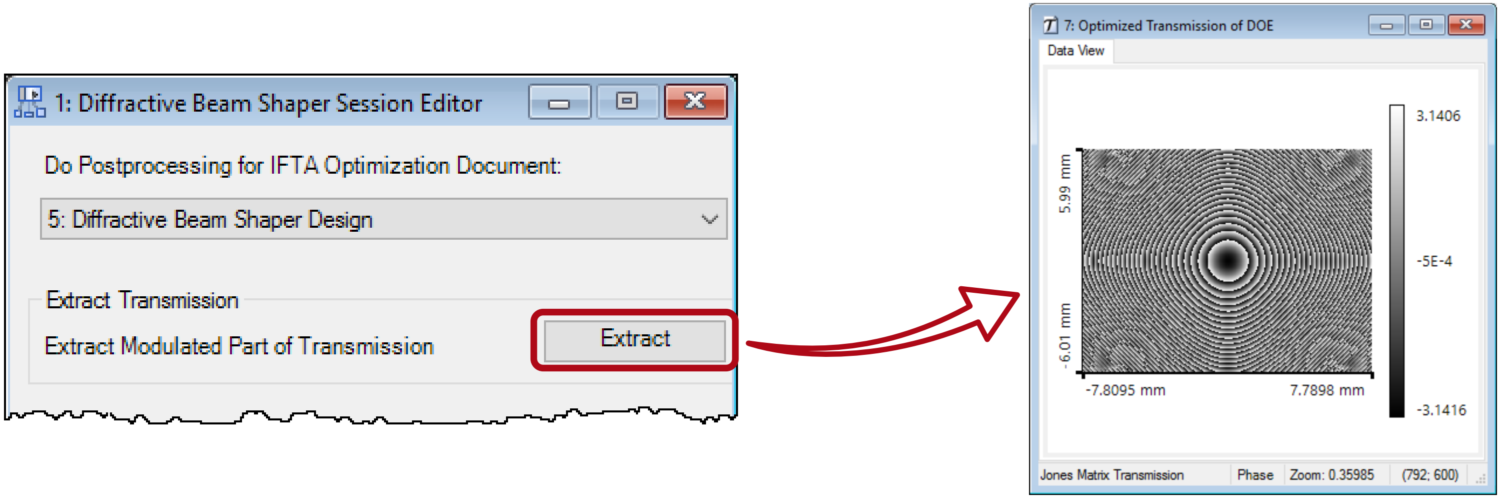
- Then click *Show Light Path* to get the corresponding Light Path Diagram (LPD).
- It is a Diffractive Optics Toolbox LPD which we will later convert to a Start Toolbox LPD to have more options.



- Initially, the IFTA will always output a transmissive on-axis system.
- Thus, we will modify the system slightly for the final simulation of the actual geometry, later.
- First, we do the final preparations regarding the designed phase transmission data.

A1: Apply SLM Aperture

- Now, we have to extract that transmission area that corresponds to the actual SLM pixel numbers.
- This extraction is automatically done, if we click *Next* on the Diffractive Beam Shaper Session Editor – Window.
- Afterwards click *Extract* to get the designed transmission function including the specified aperture.

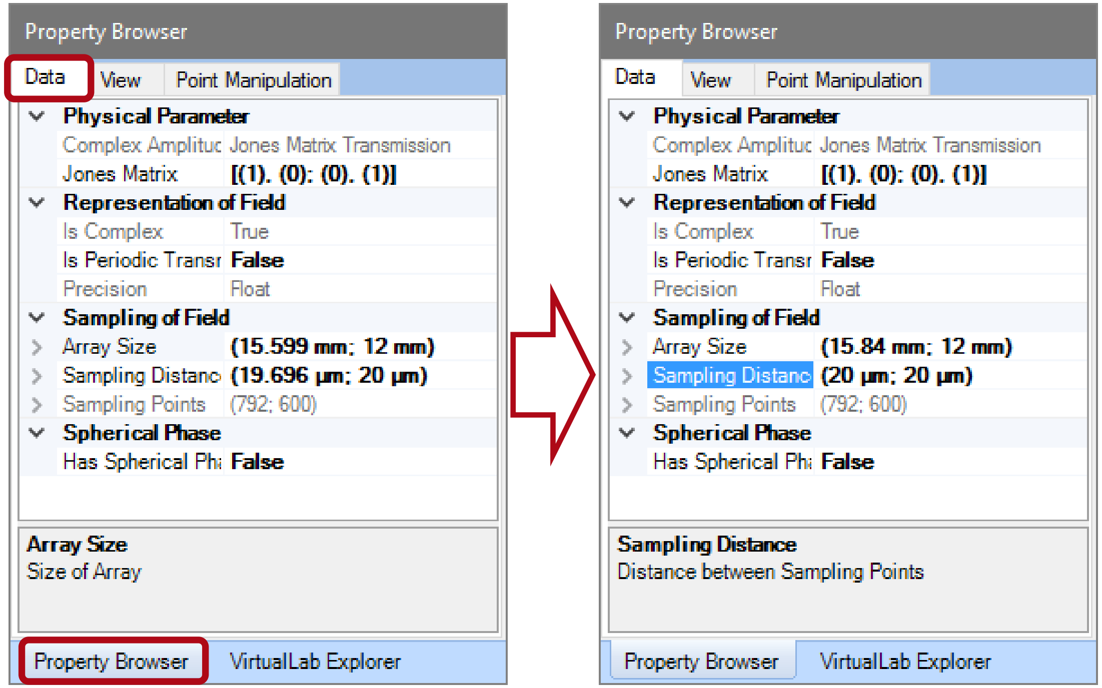


A1: Adjust Sampling Distance

- We re-adjust the sampling distance in x-direction, as this was only needed for the IFTA design. (In the total system regard the SLM has its original pixel size and its intended tilted orientation.)

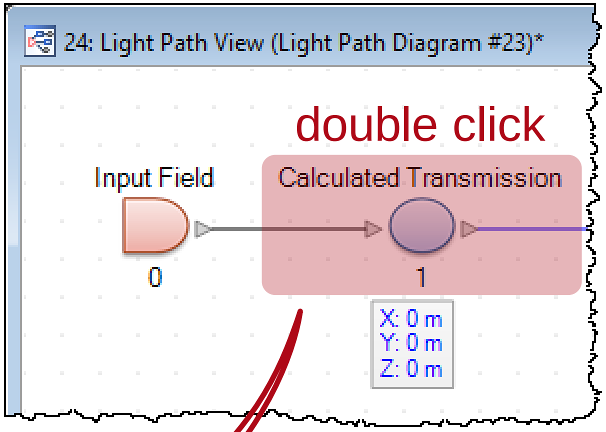
- This re-adjustment of the sampling distance is done via the *Property Browser*, in the *Data* tab.

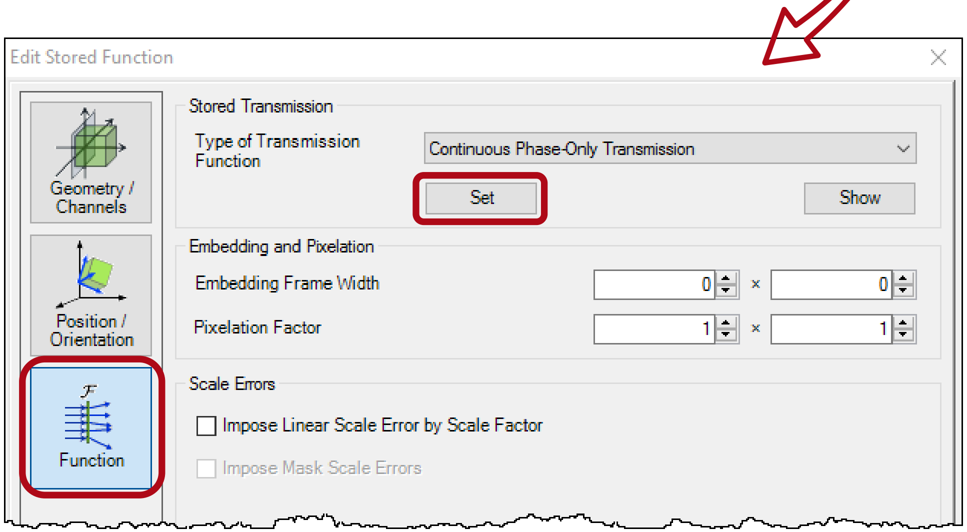
- This action would not be necessary if the whole design would have been according to an on-axis setup (transmissive or reflective with a beam splitting cube).



A1: Exchange Transmission Function

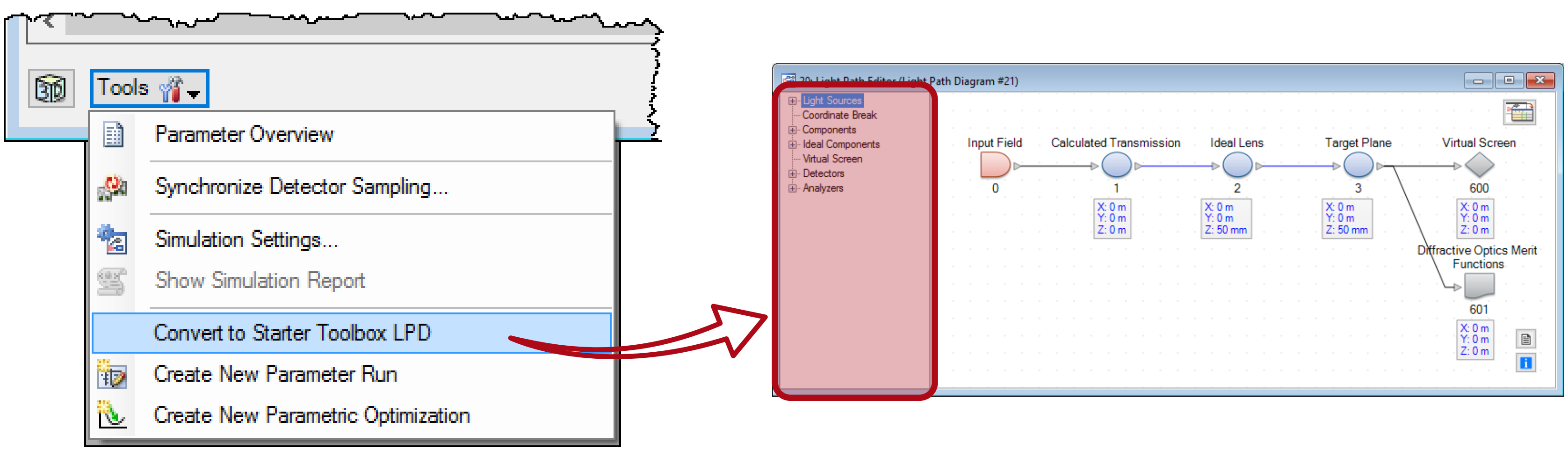
- Then exchange the stored transmission in the LPD with the adjusted one.



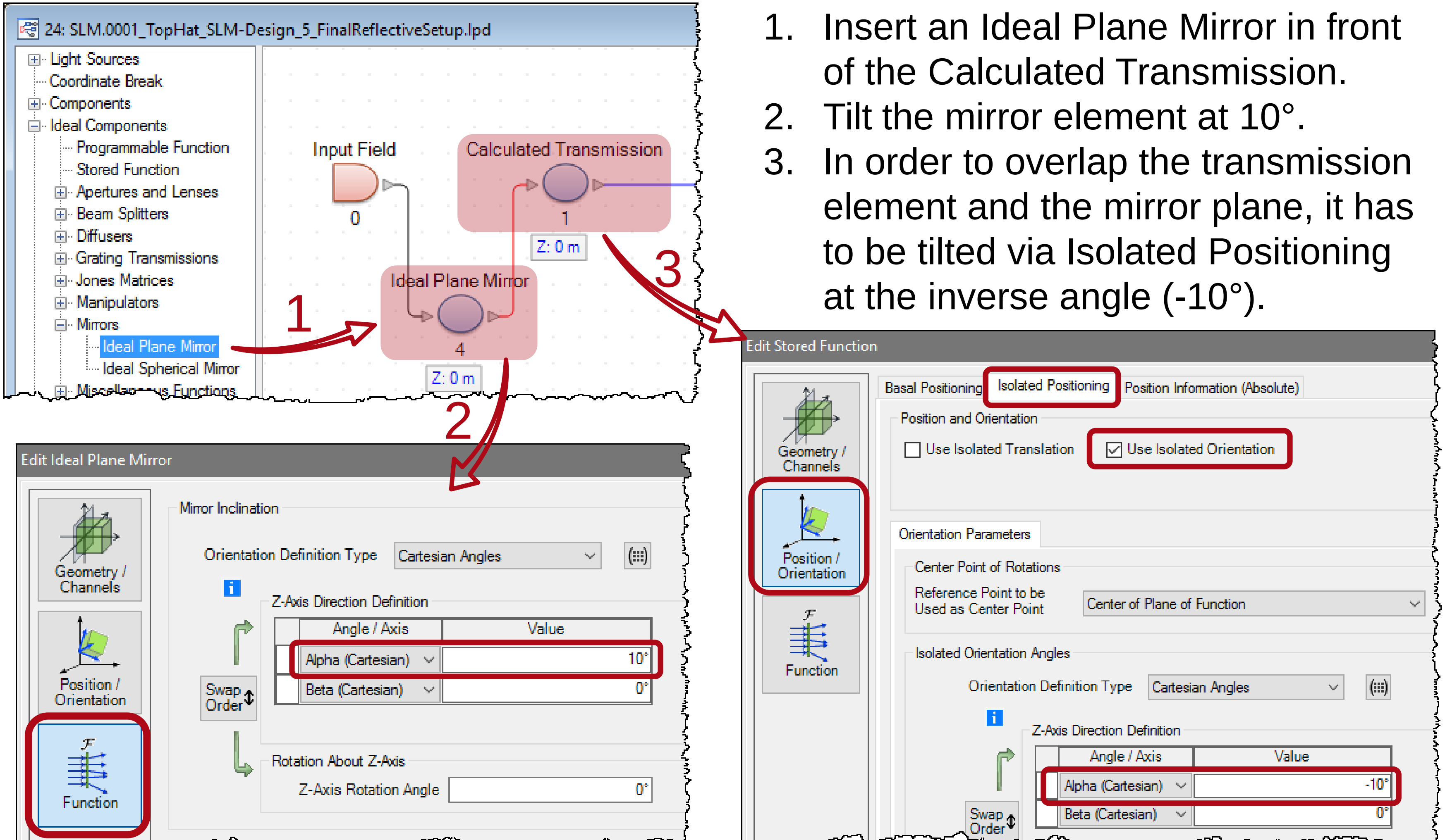


A2: Convert to Starter Toolbox LPD

- Click the *Tools* button of the light path editor of the Diffractive Optics Toolbox LPD and click *Convert to Starter Toolbox LPD*.
- By this you are getting the full select tree list of optical elements to insert.

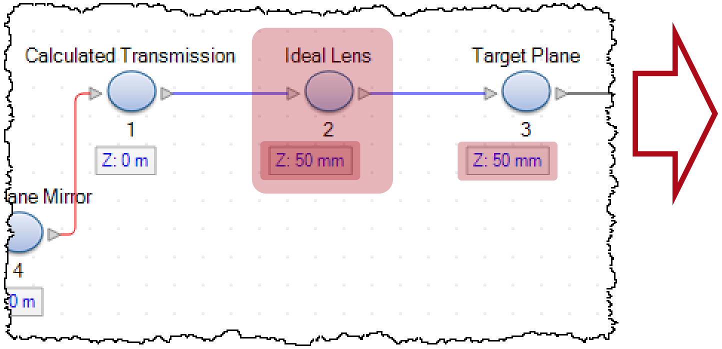


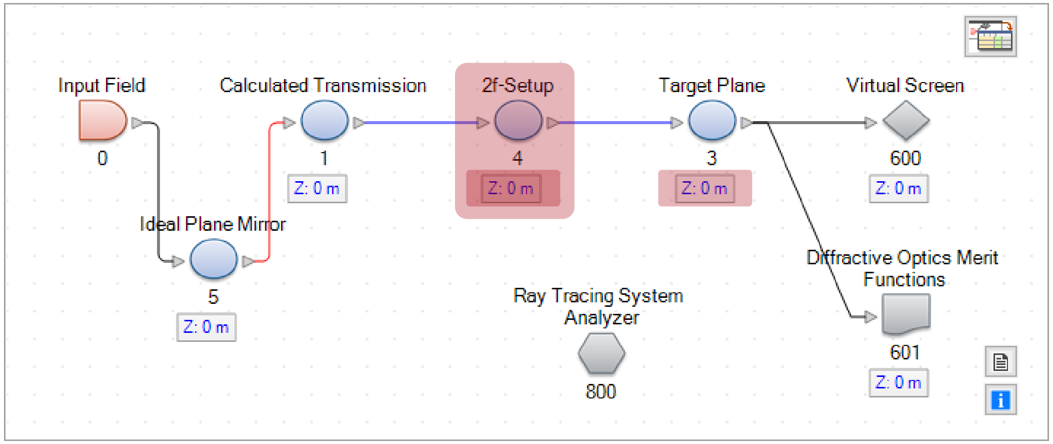
A2: Ajustments for Actual Sytems‘s Geometry



1. Insert an Ideal Plane Mirror in front of the Calculated Transmission.
2. Tilt the mirror element at 10°.
3. In order to overlap the transmission element and the mirror plane, it has to be tilted via Isolated Positioning at the inverse angle (-10°).

A3: Set 2f-Setup

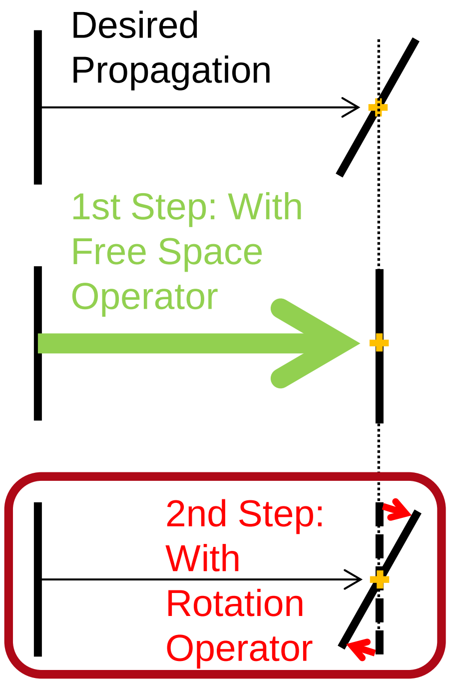


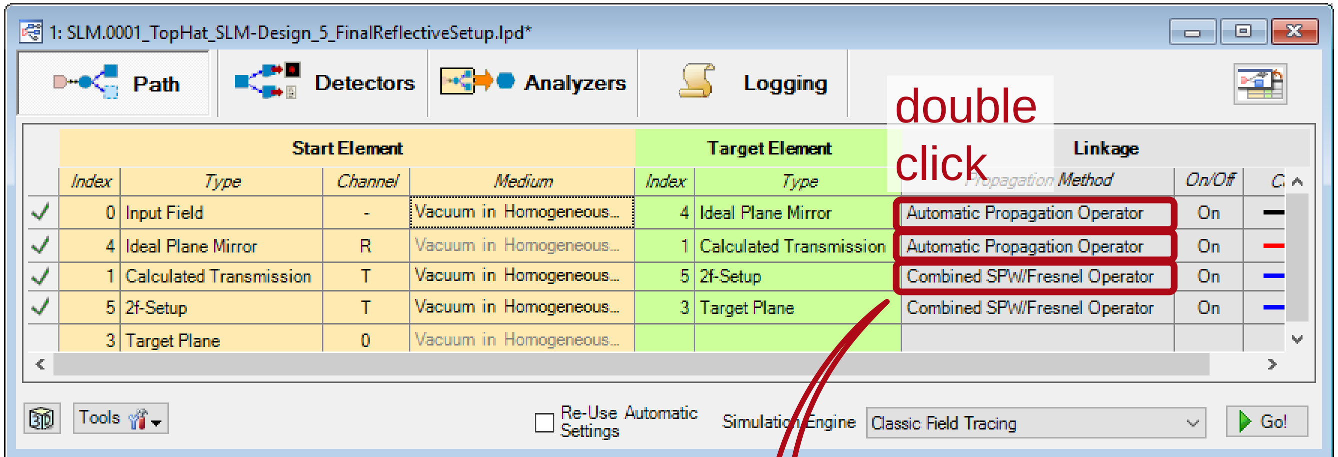


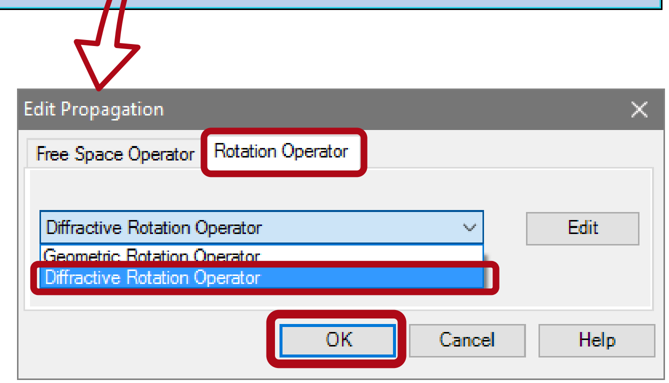
Because the **Ideal Lens** element is not appropriate for off-axis non-paraxial simulations it has to be exchanged by

- either the later intended lens in order to consider the associated aberrations
- or – as is demonstrated here – by a **2f-Setup** element, which realizes a perfect aberration free Fourier lens.
  I.e. the 2f-Setup element provides a perfect focus the deviated light to the intended positions on a plane screen, and thus compensates the non-paraxiallity. The propagation distance before and after the element are considered via a parameter setting in its edit dialog.

A3: Selection of Rotation Operator



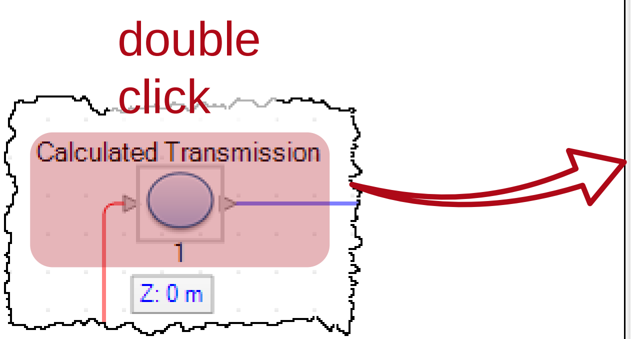


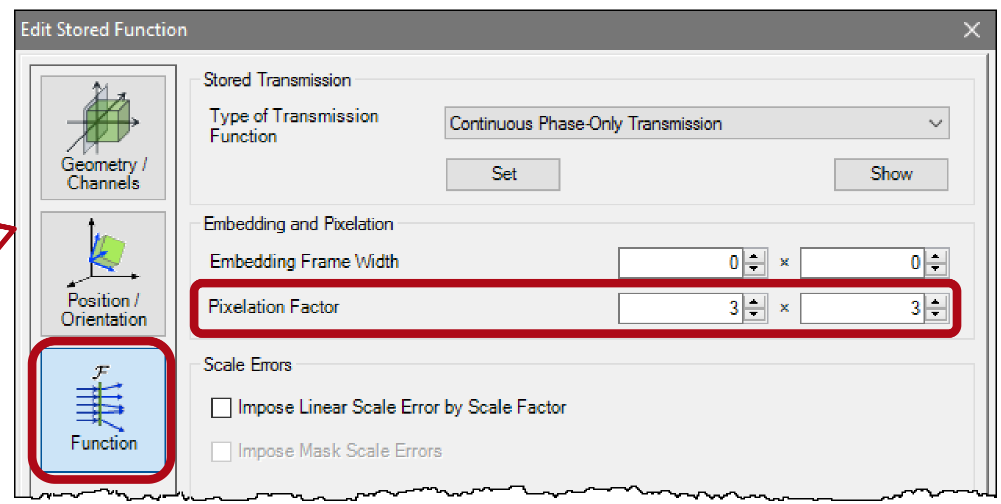


- As we are dealing with diffractive effects in the tilted planes, for the concerned elements the *Diffractive Rotation Operator* should be used.
- The smaller the SLM pixels, thus the stronger the diffraction effects, the more important is this selection.

A4: Simulation of Pixelated Transmission

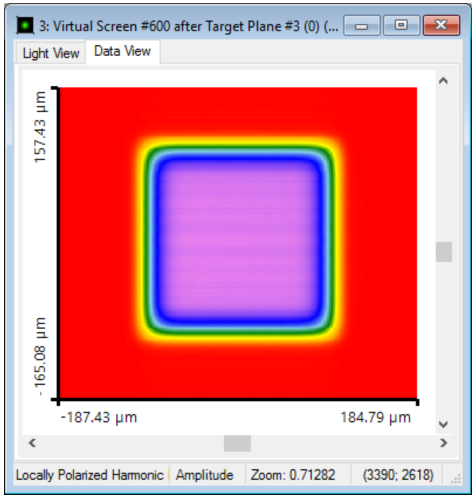
- By default, VirtualLab simulates each designed transmission pixel by one data point (simulation pixel).
- If the effect of rectangular transition (SLM) pixels should be considered each transition pixel needs to be represented by more than one data point.
- Here we simulate each of the transition pixel areas by 3x3 data points by introducing an according *Pixelation Factor*.
- Still, we do not consider gaps between the SLM pixels. Such can be regarded with a special component which is introduced in SLM.0002.
- This consideration increases the computational effort and the size of the outgoing fields.



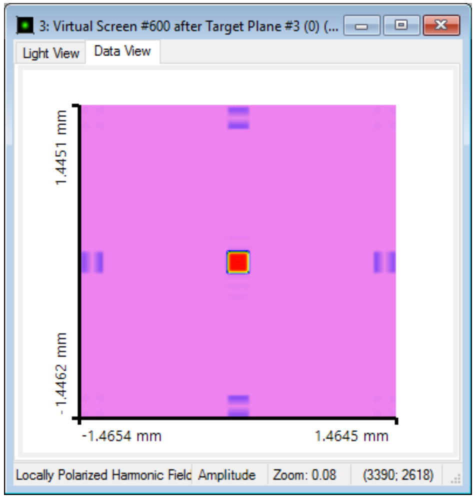


A5. Simulation of Complete Setup

1



2



Classic Field Tracing exhibits

1. the amplitude modulation within the Top Hat (rainbow color scheme)
2. the higher sinc orders due to the rectangular transmission pixels (inverse rainbow color scheme)
3. different merit function values.

3

Sub - Detector	Result
Conversion Efficiency (Classic Field	99.062 %
Signal-to-Noise Ratio (Classic Field Tracing)	47.644 dB
Uniformity Error (Classic Field Tracing)	5.7575 %
Maximum Relative Intensity of Stray Light	1.1193 %

Options & Regards Concerning Mirroring

Different Geometries, Screens & Fabrications

Consider Mirroring

Regarding the geometry of a desired setup, the user has to consider different issues when designing such a beam shaping element. For example:

- which side of the element the structure should be placed on
- if the setup is transmissive or reflective
- whether the target pattern should be seen on a transparent screen looking into the light or on an opaque screen
- how to pass on the data for further usage (manufacturer/SLM input) (what are the needed coordinate systems)

So the user might need to

- design with a mirrored pattern and/or
- use a -1 z-scaling (inversion) or a -1 x-scaling (mirroring) of the structure

to avoid mirroring effects. VirtualLab provides all necessary tools for such regards.

For the presented point-symmetric target pattern for an SLM system, no special considerations were needed.

Data Export for SLM Application

Skip

Bitmap Export

- **After the design**, the transmission data needs to be transferred to the SLM. A common method is to convert the data into the bitmap (BMP) file format and to actuate the SLM via graphics/display driver.

- For such **BMP export** the following steps should be considered:
  1. if **quantization** levels were introduced during the IFTA design, it can be done now according to the SLM‘s number of recognizable levels
  2. multiply with imported **SLM-Phase-Correction** file (if SLM manufacturer provides such)
  3. **move Phase to Real Part**
  4. **lift Positive**
  5. **normalize** max. value to 1
  6. **multiply** separately Real Part **by the number of recognizable levels**, e.g. 255 (→ 0 to 255)
  7. **export to BMP** (File > Export) – namely Real Part in Black White from 0 to the number of recognizable SLM levels

Export: 1. Introduce Quantization Levels

The quantization can by applied either during or after the design.

1. The introduction of equidistant data (e.g. phase) levels **during the IFTA design & optimization** causes a longer computational time.

   But for a smaller number of quantization levels, this option should be used as this process is done **very smoothly** by a smart algorithm (soft introduction).

2. If the SLM recognizes a large number of levels (i.e. almost continuous, e.g. 200) then a **hard quantization** can be applied **afterwards** via the interface with hardly a change of the transmission, thus almost unchanged merit function values.

   → This is done via *Manipulation* ribbon > *Quantization* > *Hard Quantization*

Export: 2. SLM Phase Correction

- Typically SLMs are not totally flat, that's why **some manufacturer provide a specific phase correction function**, which should be multiplied by the designed transmission function.

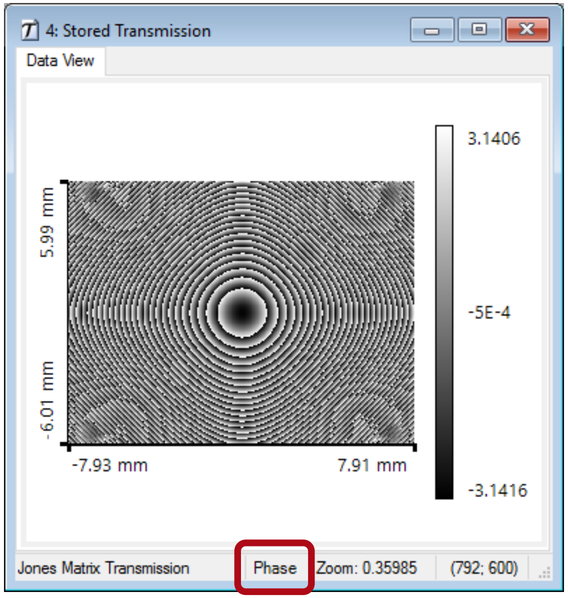
- Import the correction function and multiply it with the calculated transmission, using the "*" button on your keyboard or via *Manipulation* ribbon > *Array - Array Operations* > *Multiplication*

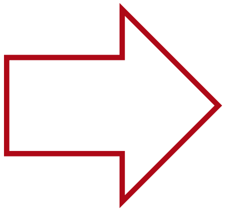
Details about Data Import in VirtualLab can be found in Tutorial 337.01.

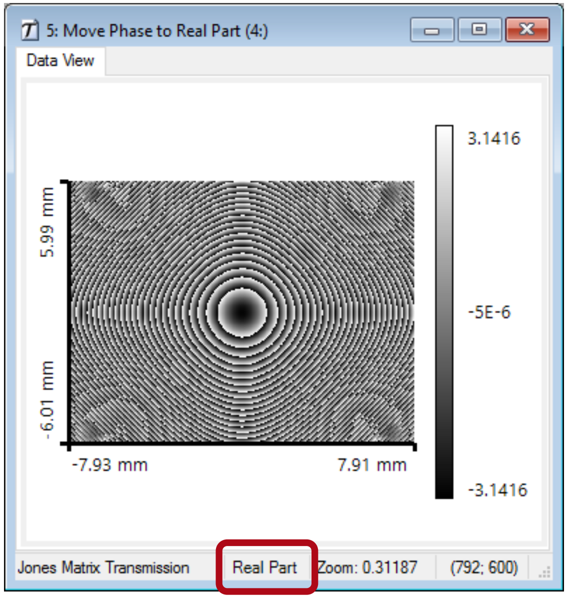
Export: 3. Phase to Real Part

Move Phase to Real Part via:

Manipulation ribbon > *Field Quantity Operation* > **Move:** *Phase to Real Part*

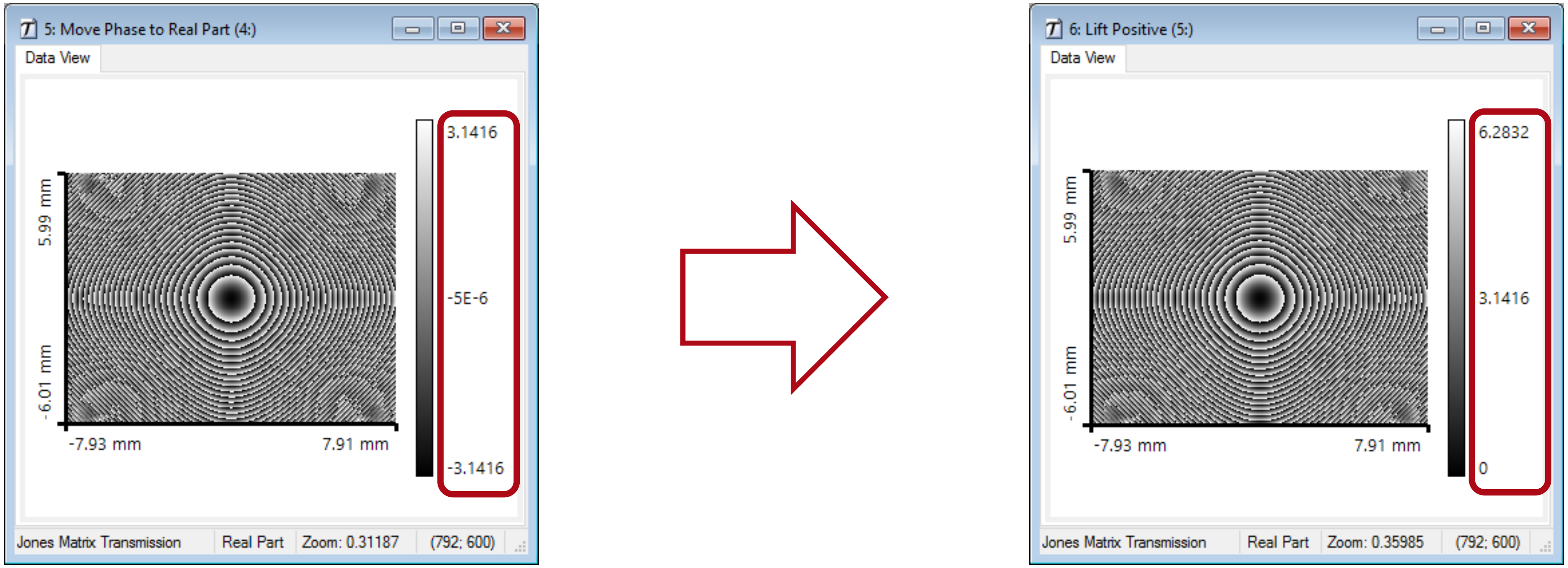






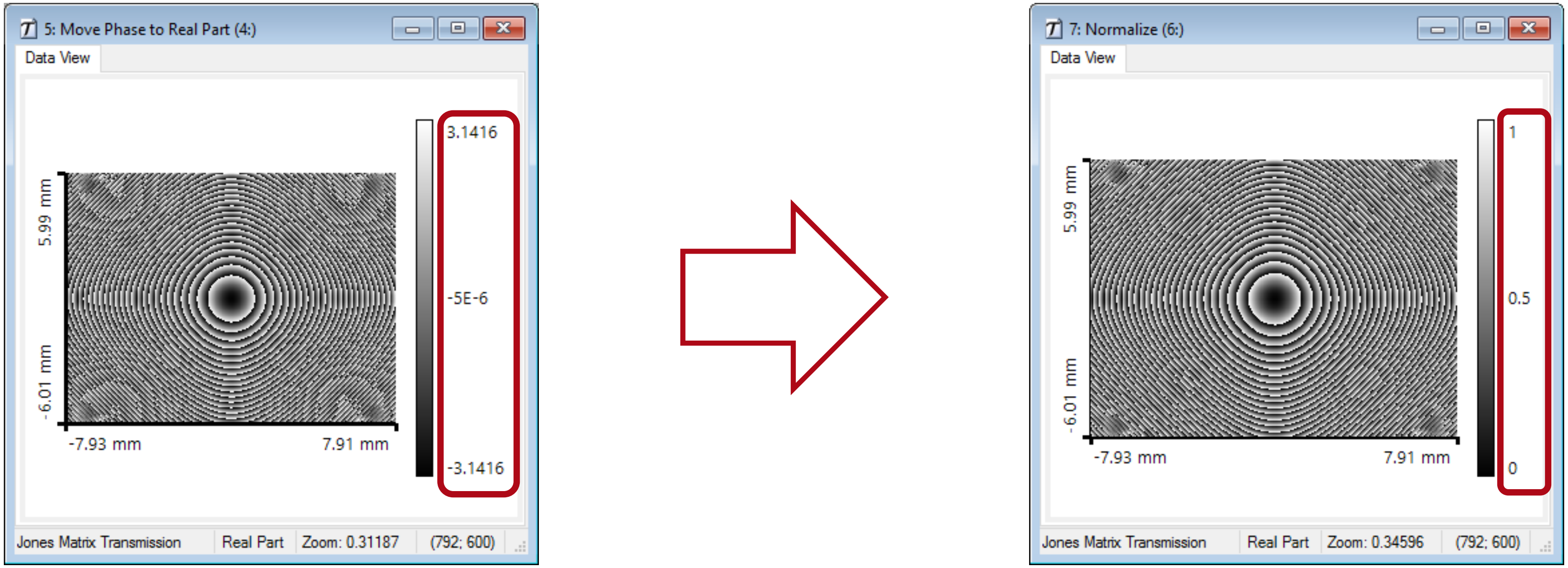
Export: 4. Lift Positiv

Via *Manipulation* ribbon > *Amplitude / Real Part Manipulations* > *Lift Positive*



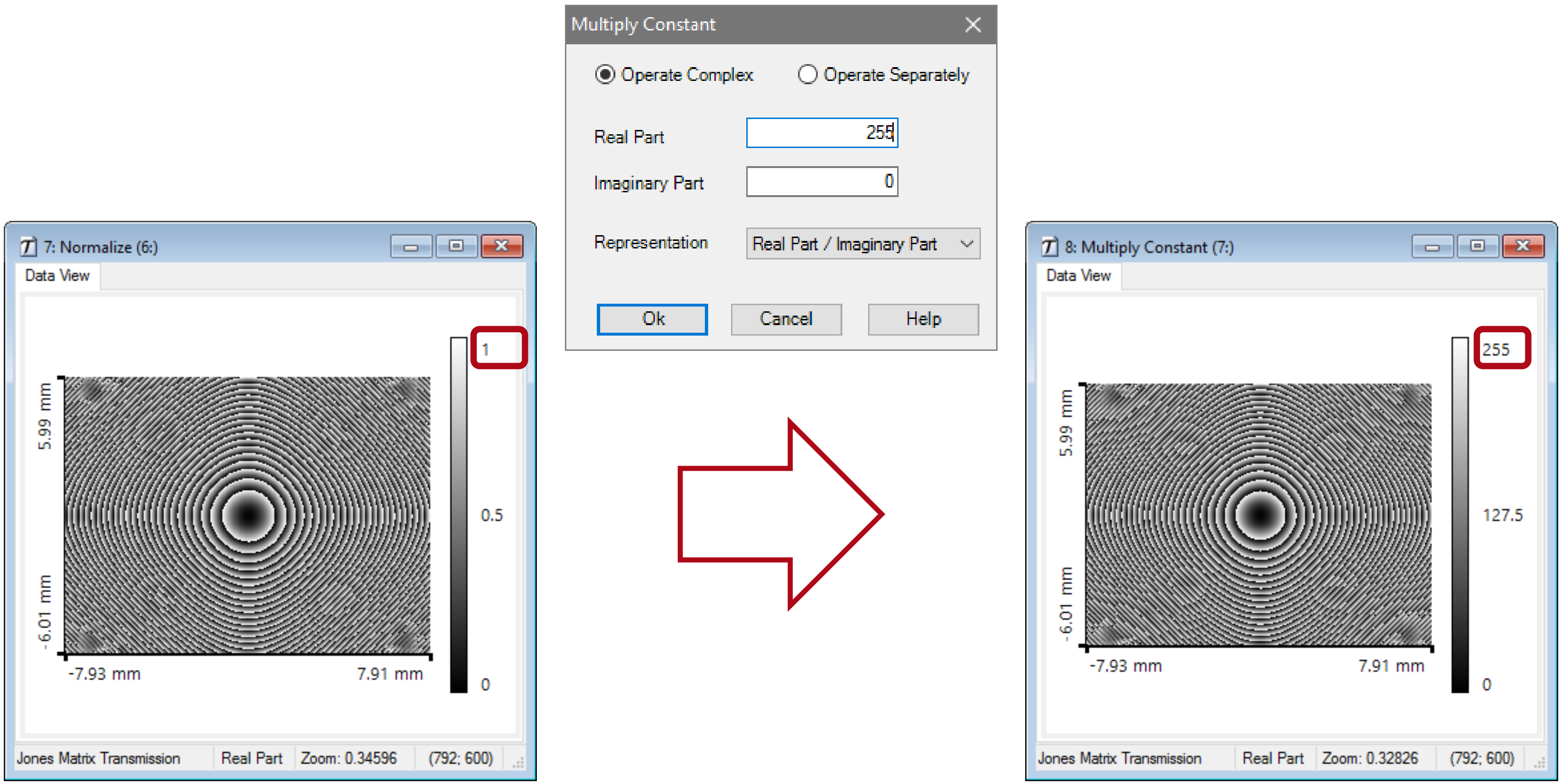
Export: 5. Normalize

Via *Manipulation* ribbon > *Amplitude / Real Part Manipulation* > *Normalize*



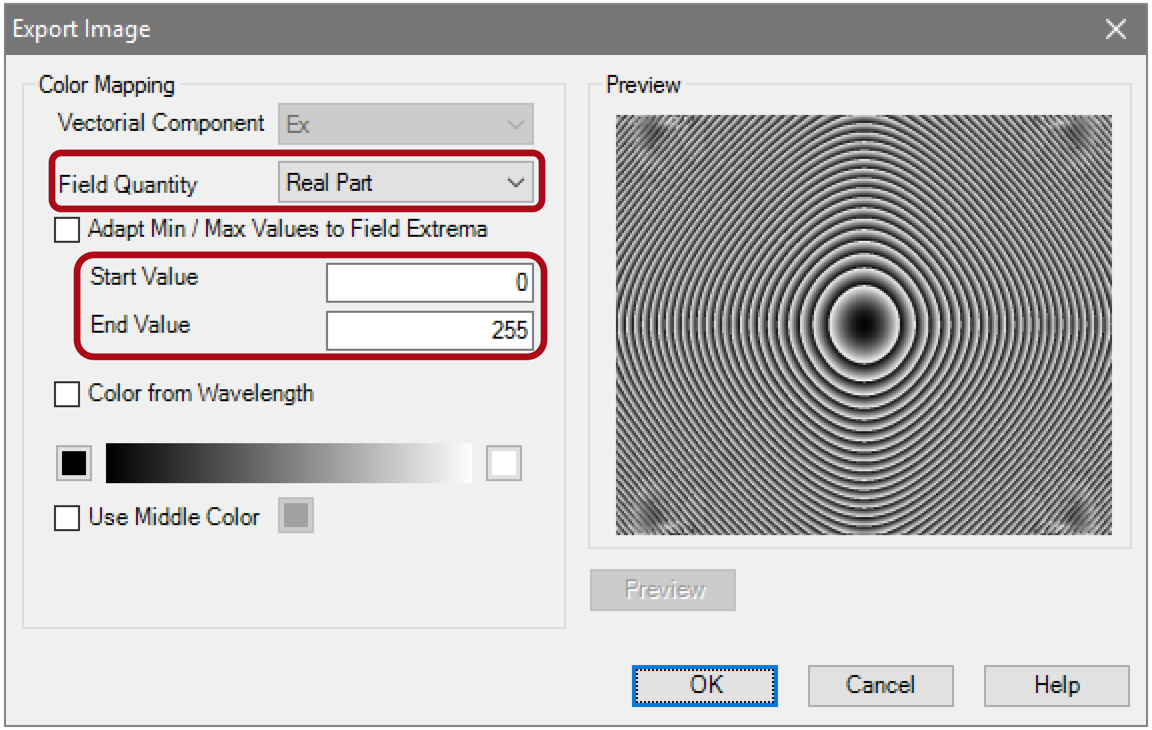
Export: 6. Adjust Maximum Value

Via *Manipulation* ribbon > *Operation with Constant* > *Multiply Constant*



Export: 7. BMP Export

Via *File* menu > *Export* > *Export as Image*



In the following export dialog change file format to .BMP.

→ Now the bitmap data can be transferred to the SLM module!

Further Readings

Further Readings

- Get Started Videos
  - Introduction to the Light Path Diagram
  - Introduction to the Parameter Run
  - Introduction to Parametric Optimization

- Documents Related with This Application Example
  - Tutorial 337: Introduction to the Data Array Import
  - SLM.0002: Simulation of Light Diffraction at Pixels of an SLM
  - SLM.0003: Investigation of Lens Aberrations in an SLM-based Beam Shaping Setup