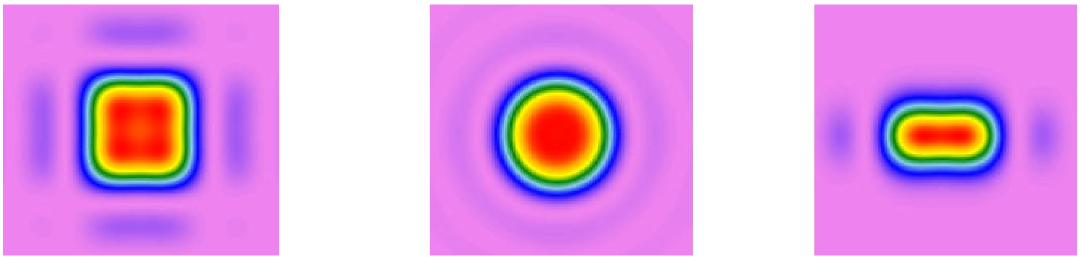


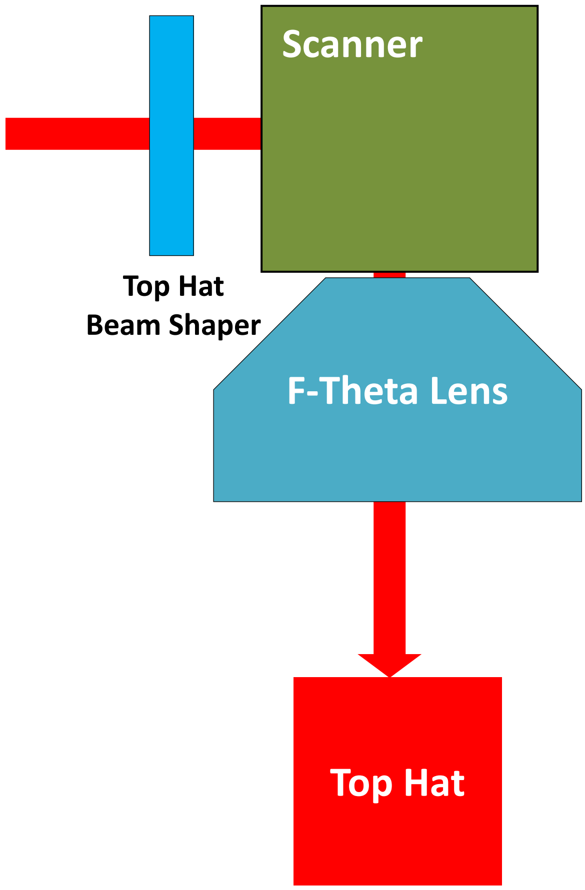
Modelling optical system consisting Top Hat beam shaper and F-Theta Scanner by using physical optics model in VirtualLab Fusion Software

Authors: HOLO/OR
Date: 31/10/2016
Version: 1

Introduction

F-Theta lenses and Laser Scanner are common in laser industry in many fields, especially for material processing of large areas or wafers. F-Theta lenses allow one to maintain a diffraction limited spot size for the whole scanning field.
A Top Hat intensity distribution is also popular in the laser additive industry.
A Small Top Hat is a special kind of Diffractive Optical Element (DOE). It keeps spot size very small (Diffraction Limited Spot x 1.54 at exp^{-2}), and with an extremely narrow transfer region. The transfer region is defined as the area between exp^{-2} and 90% from peak intensity. Transfer region is a one of the key parameters for Top Hat beam shapers. Smaller transfers regions lead to steeper side walls of the processed material.
Utilizing both a Top Hat Intensity shape and an F-Theta Scanner may significantly increase manufacturing speed and the quality of the manufacturing process.

Typical setup for using Top Hat and F-Theta Scanner



The Top Hat beam shaper is placed before the scanner at some arbitrary distance, as distance doesn't influence functionality. The main concern is for clear apertures within the scanner and F-Theta to be more than ~2.2x incident beam size.

Most F-Theta lenses on the market are designed to focus an incident beam into the smallest spot size possible in the working plane. Adding Top Hat functionality to the input beam leads to undesired effects in the working plane, because the F-Theta lens isn't optimized for this condition. The straightforward solution is to define a special system that includes all variables, such as:

1. Wavelength
2. Beam size
3. Beam quality
4. Scanner's mirrors size and positions
5. Field definition
6. Target Top Hat size
7. Etc. …

But practically it's not price effective and requires diverse specialization in many fields. Alternatively, in many cases the customer already has a system with an F-Theta scanner and is interested in upgrading his optical system with a Top-Hat intensity.

In this work we want to show the effect of adding a small Top Hat to a standard F-Theta lens in different positions within scanning field.

Background

Theoretical background (mathematical, physical) from literature or our own practice.

- Information page about Small Diffractive Top Hat
- Top Hat application note on HOLO/OR's website
- Top Hat Installation manual
- Optical calculator for Diffraction Limit
- M-shaper Top Hat for scanning applications
- Free simulation tool in MATLAB for Small Top Hat with ideal lens

Materials & Methods

The unique property of a small Top Hat is that geometrical rays “can’t see it”, because its effect is below to geometrical optics sensitivity (< wave). This leads to a demand to use more precise methods of optical simulation, such as physical optics. Physical optics considers the complex nature of the light wave and allows achieving results that are closer to the real world, compared to a purely geometrical model. A Small diffractive Top Hat diffracts the incident beam only slightly, but this is enough for the desired functionality of beam shaping. VirtualLab is the natural choice for complex optical simulation where diffraction and interference effect are considered. Its propagation methods are optimized for systems where classical refractive elements meet diffractive elements.
In this report we will compare physical optics results with those of geometrical optics.

Specification of F-Theta lens used for the demonstration:

- Scan field ± 15^o
- Wavelength 532 nm
- EFL 100 mm
- Working Distance 127.55 mm
- Optimized to Gaussian Beam <3 mm (exp^{-2})
- Clear aperture 6.25 mm
- Glass material BK-7

Diffractive Top Hat elements to be examined in the report:

PN	Shape	Nominal beam size	Direct link to product page
ST 293	Square	3 mm	Link
ST 260	Round	3 mm	Link
ST 268	Line	3 mm	Link

List of simulations:

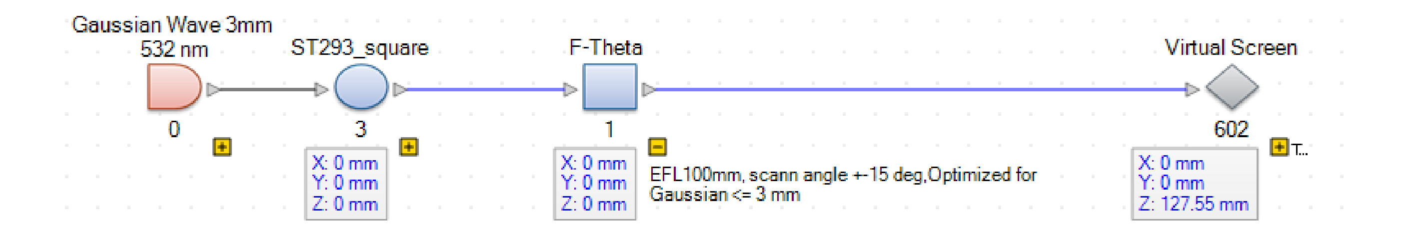
1. Simulation of the system without Top Hat beam shaper
2. Intensity distribution in central position, middle and maximum scanning field with Top-Hat beam shaper
3. Effect of using smaller than recommended clear aperture

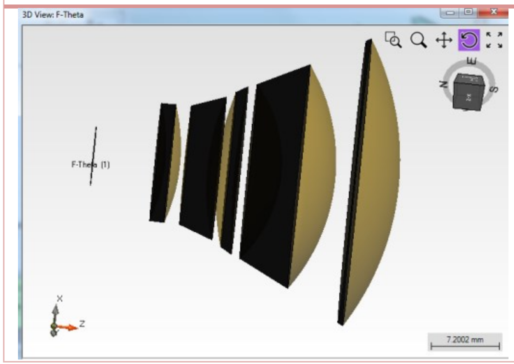
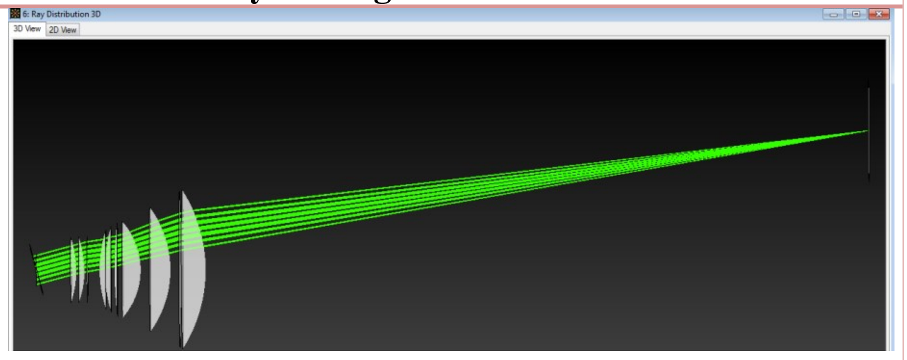
Results

The optical setup includes:

1. Gaussian beam TEM00 3 mm diameter (exp^{-2})
2. Top Hat DOE
3. F-Theta lens (built from 5 lenses BK7)
4. Virtual screen as detector

Print screen of the optical setup in VirtualLab



F-Theta Lens 3D view	**Geometrical ray tracing 3D view**
	

Diffraction limit calculation with HOLO/OR calculator (Diffraction limited Spot Size):

http://holoor.co.il/Diffractive_Optics_Products/Calculators.htm

Beam size without Beam Shaper

Diffraction-Limited Spot Size Calculator

Wavelength	532	nm
Effective Focal Length (EFL)	100	mm
Beam Diameter (D)	3	mm
Laser Beam Quality (M^2)	1	
Diffraction-Limited Spot size (ω_0)	22.58	um

Calculated Top Hat size

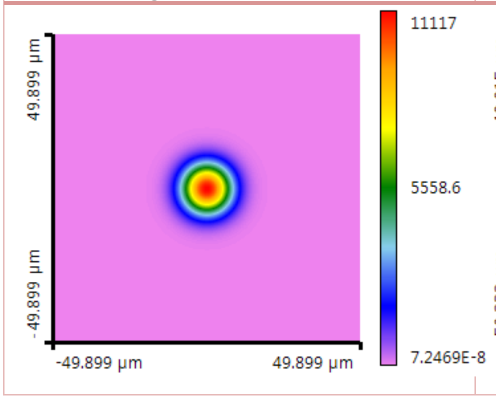
Diffraction-Limited Spot Size Calculator

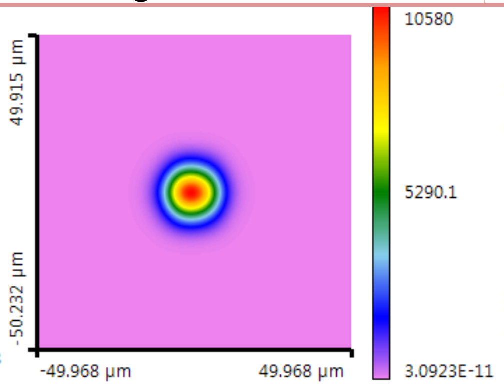
Wavelength	532	nm
Effective Focal Length (EFL)	100	mm
Beam Diameter (D)	3	mm
Laser Beam Quality (M^2)	1.54	
Diffraction-Limited Spot size (ω_0)	34.77	um

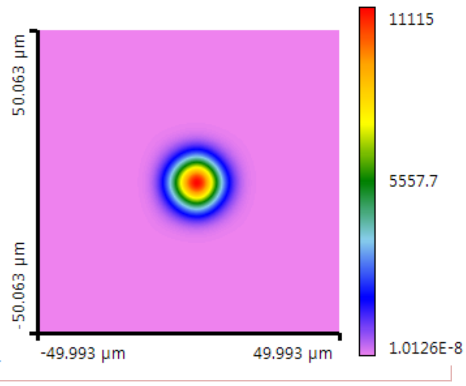
Field tracing propagation results for different angles

Propagation of Gaussian beam 3 mm through F-Theta without Top Hat DOE, Clear Aperture 6.25 mm

Scan Angle 0^{o}	Scan Angle 7.5^{o}	Scan Angle 15^{o}





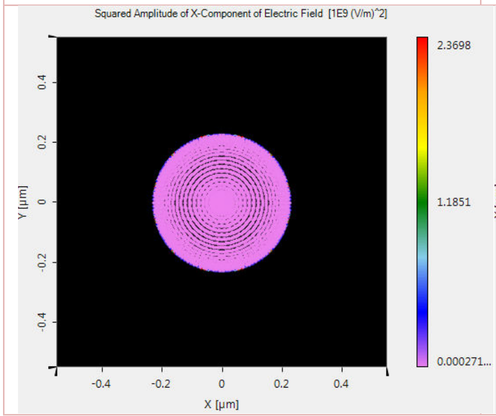


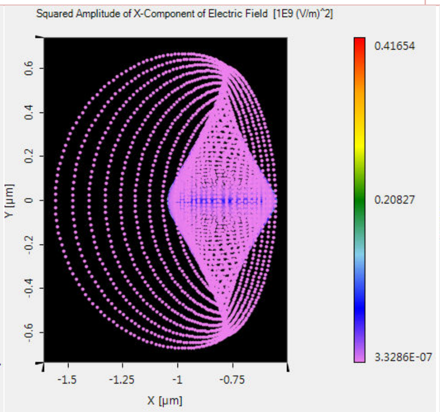
Scan Angle in degrees (Cartesian)	0	7.5	15
Beam size radius X [um]	11.29	11.46	11.51
Beam size radius Y [um]	11.31	11.46	11.58
Deviation from theory X [%]	0.0	1.5	2.0
Deviation from theory Y [%]	0.1	1.5	2.6

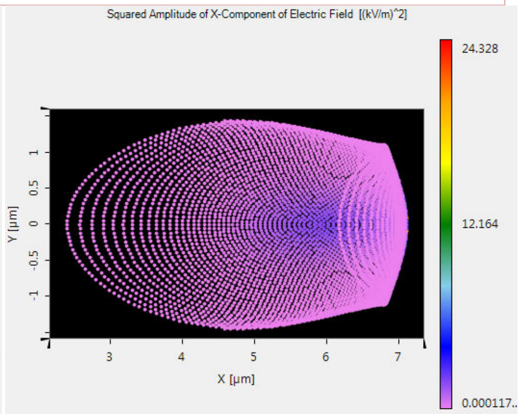
Geometrical ray tracing for F-Theta lens. Airy Radius: 8.653 µm

Geometrical Rays Tracing in VirtualLab

Field 0^{o}	Field 7.5^{o}	Field 15^{o}



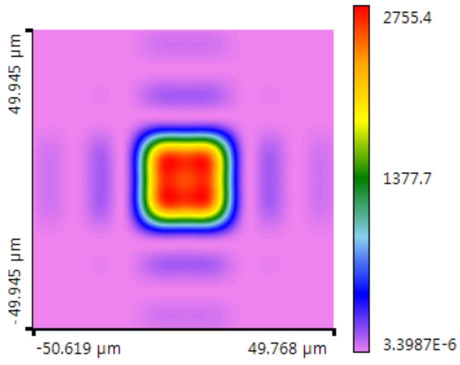




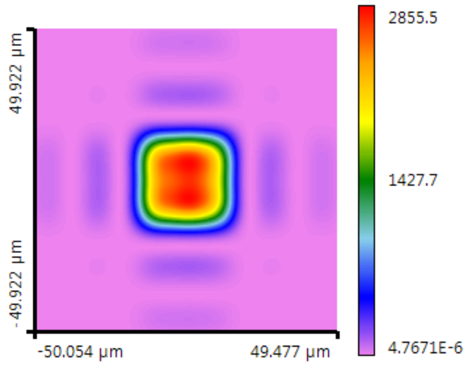
Geometrical raytracing shows spot size is Diffraction limited for tested scan angles.

Propagation of Gaussian beam through ST 293 Top Hat DOE square shape and F-Theta lens

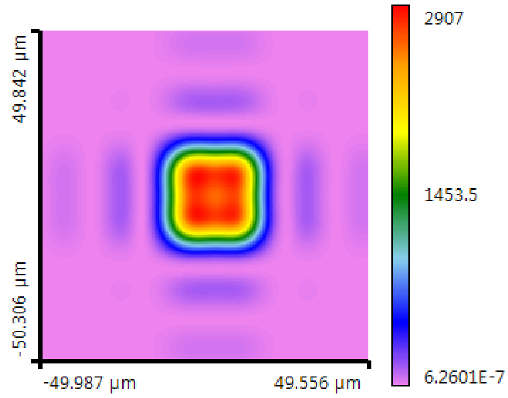
Angle 0, 0



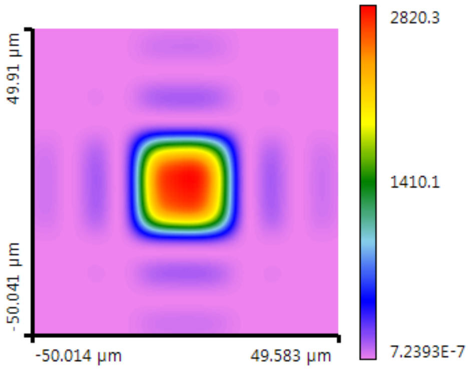
Angle 7.5, 0



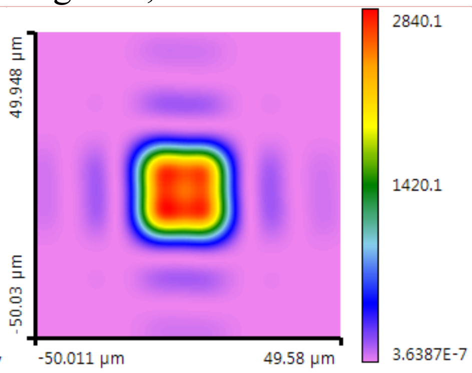
Angle 15, 0



Angle 7.5, 7.5

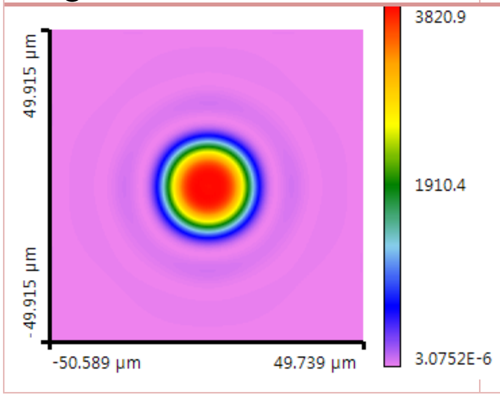
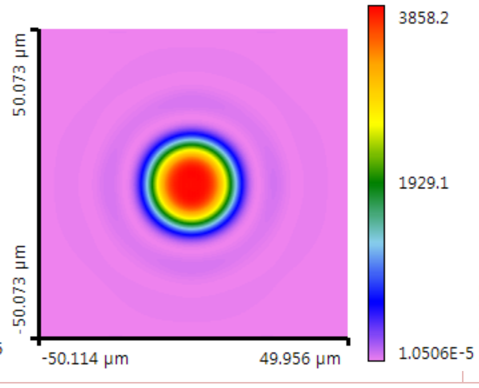
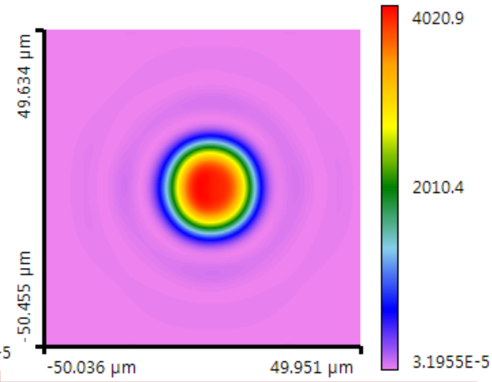


Angle 15, 15



Scan Angle in degrees (Cartesian)	0	7.5	15	7.5, 7.5	15, 15
Beam size radius X [um]	17.00	16.92	16.81	17.02	16.98
Beam size radius Y [um]	17.00	17.04	17.14	17.04	16.98
Deviation from field 0 X [%]		0.2	0.8	0.2	-0.1
Deviation from field 0 Y [%]		0.3	0.8	0.2	-0.1

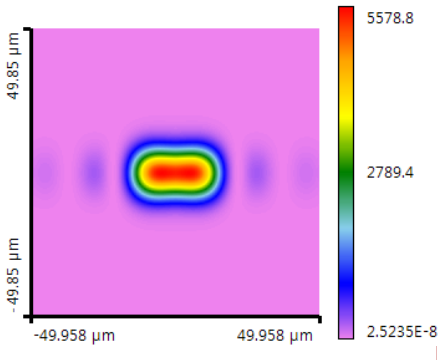
Propagation of Gaussian beam through ST 260 Top Hat DOE round shape and F-Theta lens

Angle 0	Angle 7.5	Angle 15
		

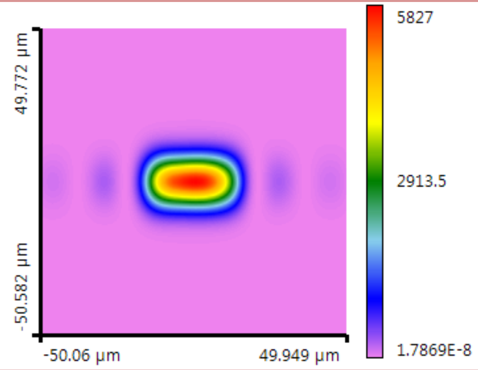
Scan Angle in degrees (Cartesian)	0	7.5	15
Beam size radius X [um]	17.99	17.89	17.89
Beam size radius Y [um]	17.96	17.99	18.12
Deviation from field 0 X [%]		-0.6	-0.5
Deviation from field 0 Y [%]		0.2	0.9

Propagation of Gaussian beam through ST 268 Top Hat DOE line shape and F-Theta lens

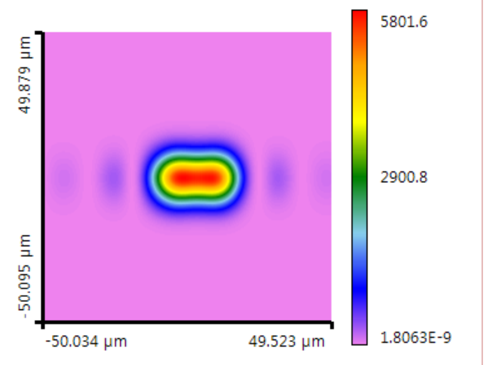
Angle 0, 0



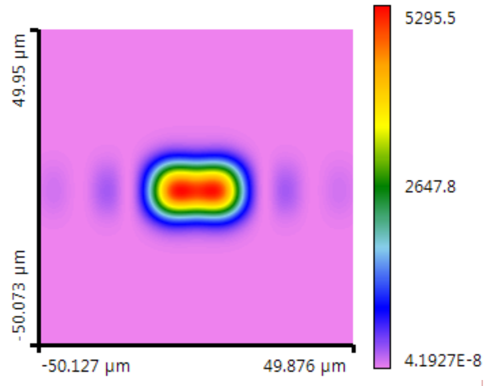
Angle 7.5, 0



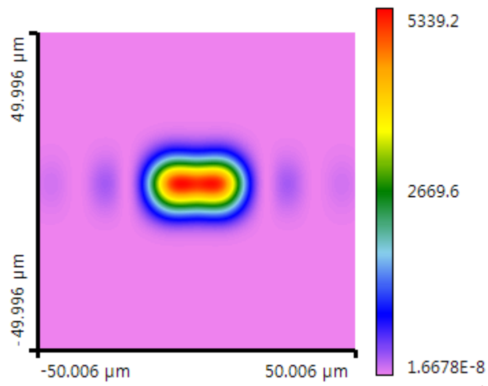
Angle 15, 0



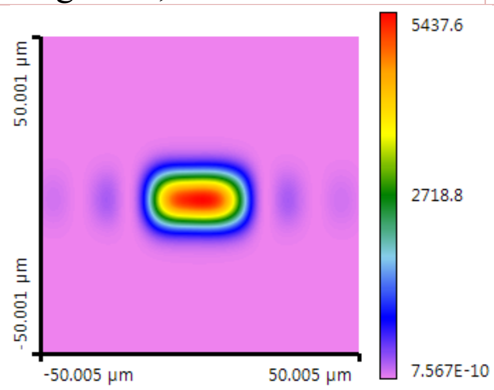
Angle 0, 7.5



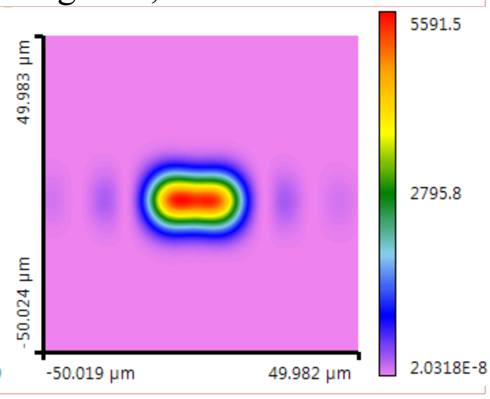
Angle 0, 15



Angle 7.5, 7.5



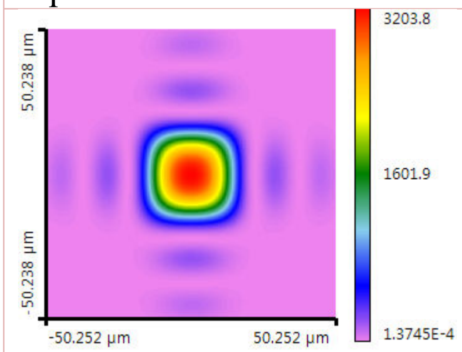
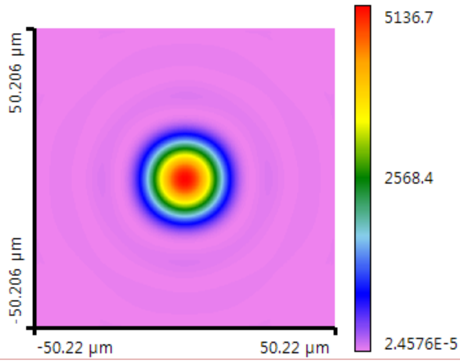
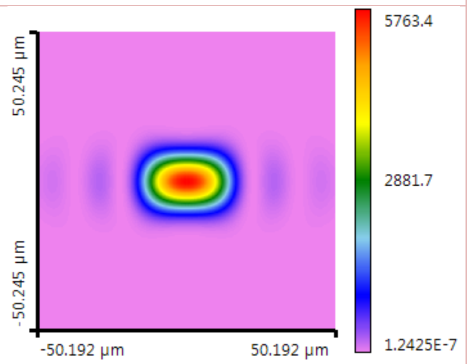
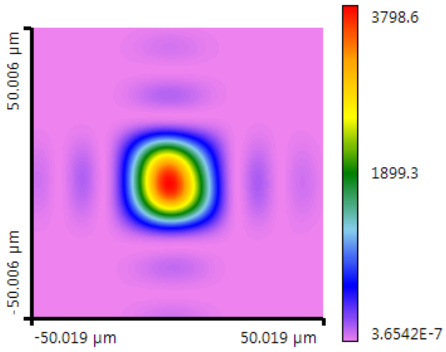
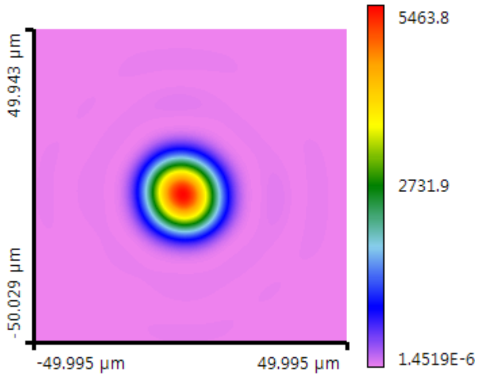
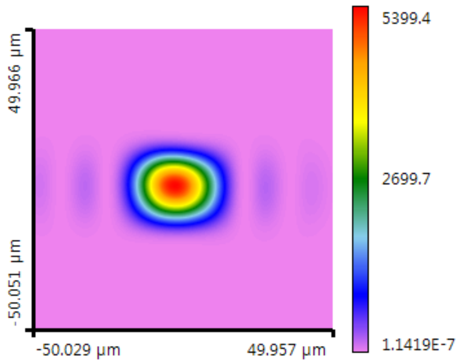
Angle 15, 15



Scan Angle in degrees (Cartesian)	0, 0	7.5, 0	15, 0	0, 7.5	0, 15	7.5, 7.5	15, 15
Beam size radius X [um]	16.98	16.87	16.76	16.92	17.05	16.95	16.92
Beam size radius Y [um]	11.29	11.33	11.56	11.47	11.50	11.46	11.57
Deviation from field 0 X [%]		-0.6	-1.3	-0.3	0.4	-0.1	-0.4
Deviation from field 0 Y [%]		0.3	2.4	1.6	1.8	1.5	2.5

Insufficient clear aperture effect

The results below show the effect that occurs when F-Theta lens or/and scanner have a clear aperture smaller than recommended. This example is of clear aperture 4.5 mm (1.5 x beam size).

<table>
<tr><td colspan="3">Angle (0, 0). Beam size without DOE 12.19x12.2 um</td></tr>
<tr><td>Square</td><td>Round</td><td>Line</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Beam size radius: 16.75x16.70 um</td><td>Beam size radius: 14.64x14.53 um</td><td>Beam size radius: 16.55x11.8 um</td></tr>
<tr><td colspan="3">Angle (15, 15). Beam size without DOE 12.99x12.96 um</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Beam size radius: 16.17x16.26 um</td><td>Beam size radius: 14.16x14.20 um</td><td>Beam size radius: 16.03x12.7 um</td></tr>
</table>

Analysis

1. F-theta lens in geometrical optics is diffraction limited. In physical optics the spot is also diffraction limited but its shape is a slightly imperfect Gaussian. That imperfection also has a slight effect on the Top Hat shape. The size of Top Hat remains constant for a defined scan field.

2. A Round Top Hat is less sensitive to scan field than a square or a line shape. Still, the overall effect on all shapes for different field angles is very limited. Naturally, for applications with scanning along all directions round shape will give best results. A Square shape will be better for orthogonal scans and line shape better for 1D scanning applications.

3. In the report we examined the case of using a small clear aperture along the optical axis. This refers to the entrance pupil size, clear apertures of mirrors and the clear aperture of F-Theta lens. Cutting the beam by an aperture < ~2.2 times beam diameter will cause boundary diffraction creating an undesired effect on the beam shaper functionality. Mainly, transfer region will increase while flat area will be reduced.

4. It seems reasonable to define an F-Theta scanner as fits to work with a small Diffractive Top Hat, when one measures a Gaussian spot size in focal plane close to theoretical value without the beam shaper.

5. We do not recommend using Small Top Hat for lasers with $M^2 > 1.3$, because it's functionality is very close to the deviation of the laser beam from ideal Gaussian.

Conclusion

In the current report we showed that a small diffractive Top Hat beam shaper works well in combination with an F-Theta scanner. The specific parameters of the F-Theta lens must be considered when choosing the correct beam shaper. The Field tracing simulation method in VirtualLab allows one to combine the classic refractive elements of F-Theta lens with fully diffractive elements and to demonstrate diffraction and interference effects for different scan angles.

References

F-theta Lens links

1. Handbook of Optical and Laser Scanning, Second Edition. By Gerald F. Marshall, Glenn E. Stutz

   https://books.google.co.il/books?id=PJjLBQAAQBAJ
2. Lens Design, Fourth Edition. By Milton Laikin
   https://books.google.co.il/books?id=wN_sn_sRs_YC

Top Hat links

3. Laser Beam Shaping: Theory and Techniques, Second Edition edited by Fred M. Dickey
   https://books.google.co.il/books?id=Ph_cBQAAQBAJ
4. Diffractive Optics: Design, Fabrication, and Test. By Donald C. O'Shea
   https://books.google.co.il/books?id=NFrG-zFrIDYC

Simulation Software

5. VirtualLab software
   http://www.wyrowski-photonics.com