Holographic surface diffusers

Fabrication, measurement and simulation of

stochastical surfaces for scattering purposes

Tobias Kraus, April 2022

Overview

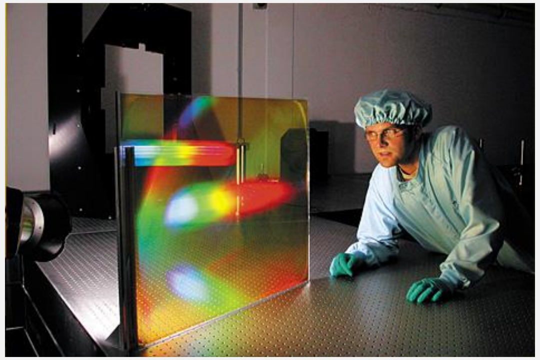
- A brief overview of temicon‘s capabilities
- Interference lithography
- Fabrication of stochastical surfaces and degrees of freedom
- Well defined statistical means of stochastical surfaces
- Optical properties and simulation approaches
- Summary & Outlook

A brief overview of temicon‘s capabilities

A brief overview of temicon's capabilities

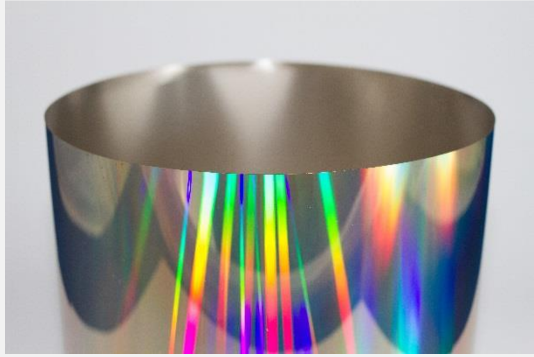
Lithography

UV Lithography



Laser Interference Lithography

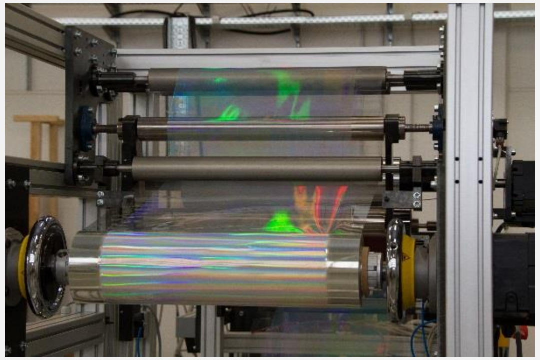
Tooling



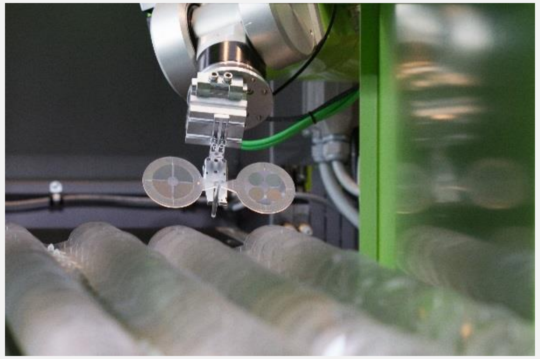
Electroforming Sleeves

Electroforming Shims, Inserts

Replication



Roll-to-Roll, Roll-to-Plate

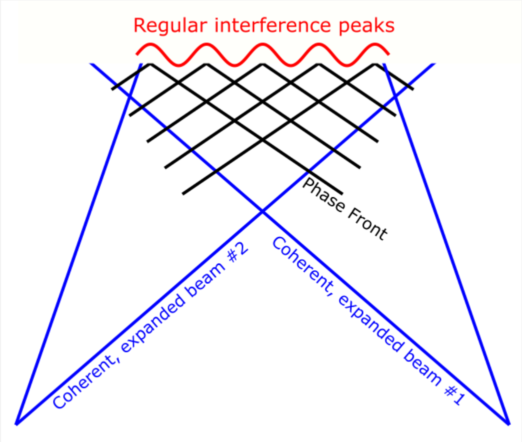


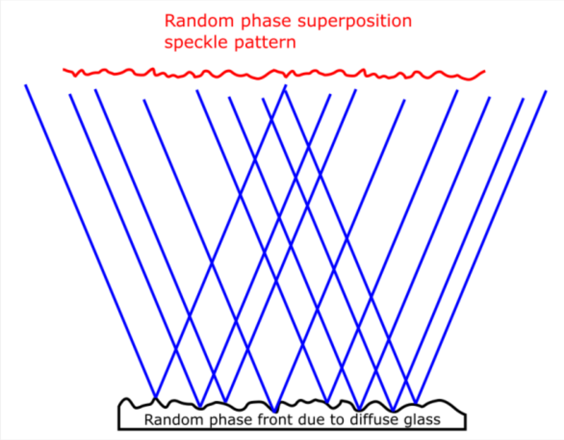
Injection Molding

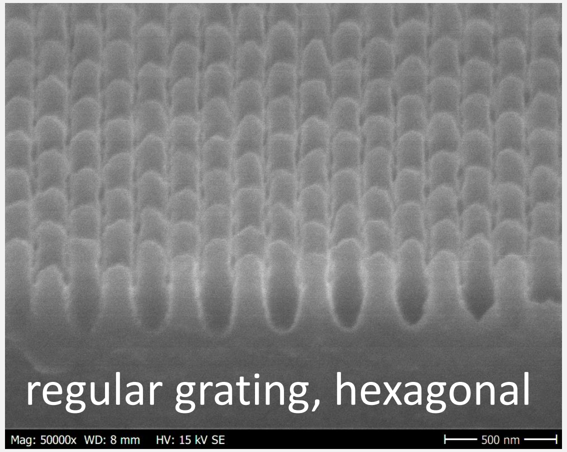
Interference lithography

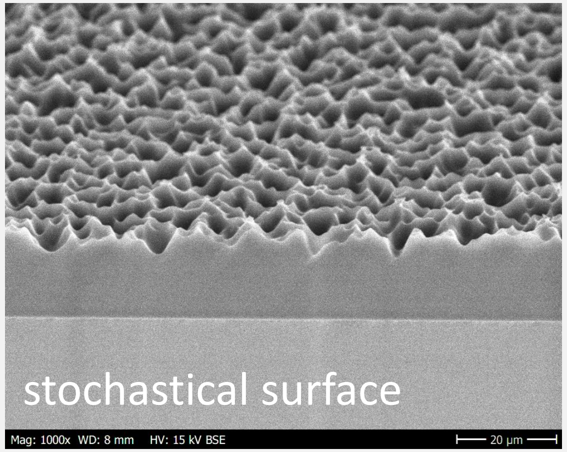
Interference lithography

- Coherent two-, three- or random phase multiwave superposition leads to distinct interference patterns in light field
- Recording of „nanostructured light field“ into photosensitive material (up to 20“ x 24“ or even larger)
- Development of photoresist leads to topographical surface
- Line gratings, crossed gratings and hexagonal gratings are possible
- Stochastical surfaces will be covered in this talk (Random phase speckle pattern)









Fabrication of stochastical surfaces and degrees of freedom

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Fabrication of stochastical surfaces and degrees of freedom

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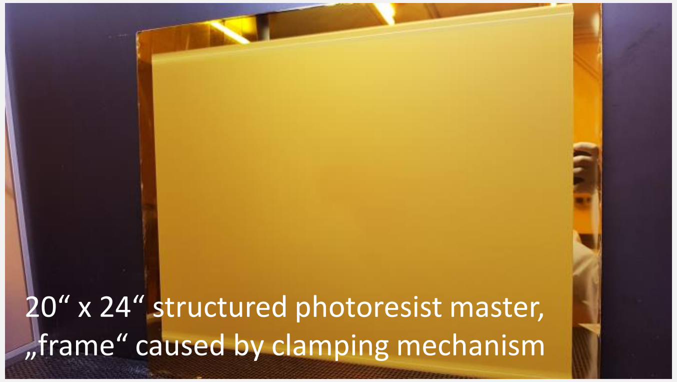
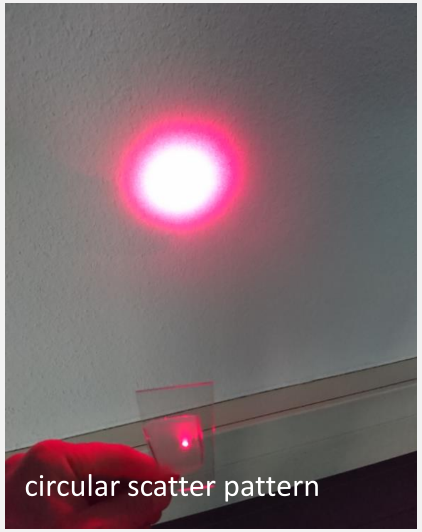
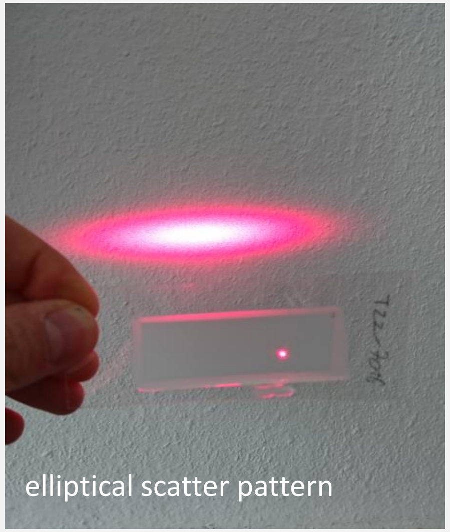
- Fabrication
  - » Speckle field due to random phase shift caused by primary diffuser
  - » Recording into photoresist

- Degrees of freedom of interference process caused **only** by differences in illumination setup
  - » Speckle size (Range: 3µm to 100µm)
  - » Speckle shape (Circular to quasi linear)
  - » Depth of structure (1µm to several 10µm)

- Possible scatter patterns
  - » Gaussian scatter shapes are circular, elliptical, linear
  - » Scatter width from 1° FWHM to 125° FWHM
  - » Very high quality surface (no unwanted roughness)


20“ x 24“ structured photoresist master, „frame“ caused by clamping mechanism

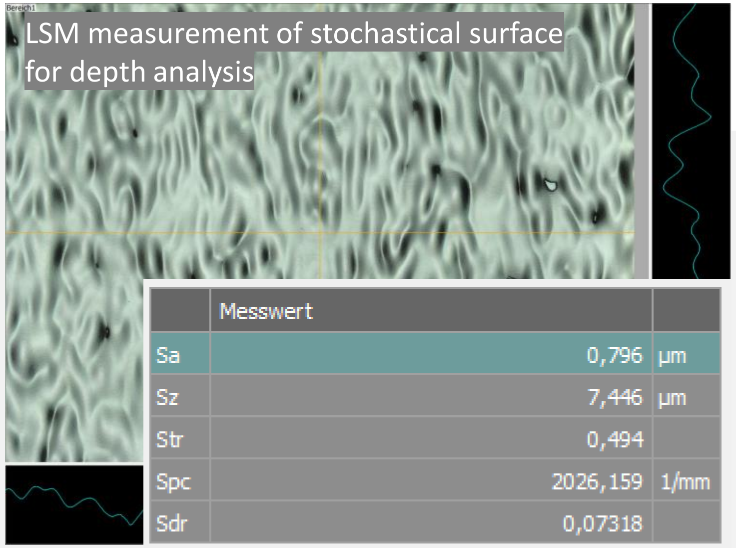

circular scatter pattern


elliptical scatter pattern

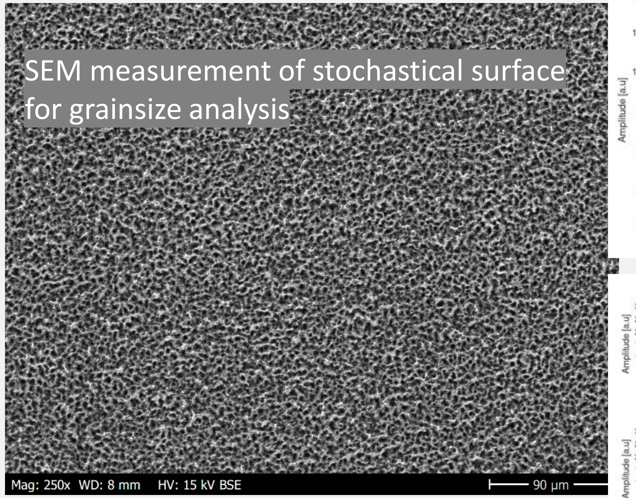
Well defined statistical means of stochastical surfaces

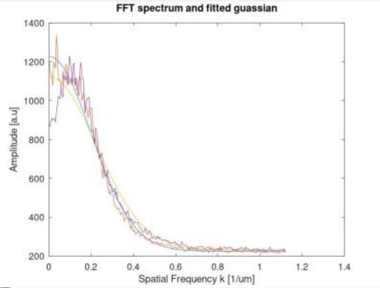
Well defined statistical means of stochastical surfaces #1

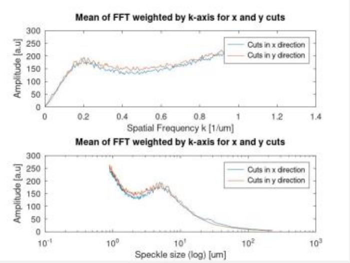
- General challenge:
  - Statistical mean gets better the higher the resolution and with increasing examined area
  - Choice of measurement method and post processing is **demanding**
- Distribution of Depth
  - Can be estimated by means of laser scanning microscope (LSM)
  - Peak-Peak, mean depth, distribution of depths can be extracted
- Grainsize
  - Various approaches possible, based on top-view SEM :
  - Peak-Counting per measured area (challenging due to noisy data and peak find algorithm)
  - Fourier transformation of gray values and calculation of most likely frequencies
  - Both approaches give similar results comparable to optical calculations in accordance to interference theory



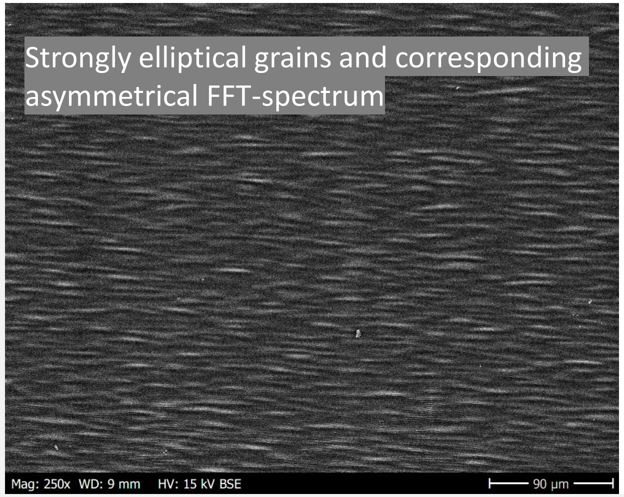
	Messwert	
Sa	0,796	µm
Sz	7,446	µm
Str	0,494	
Spc	2026,159	1/mm
Sdr	0,07318	

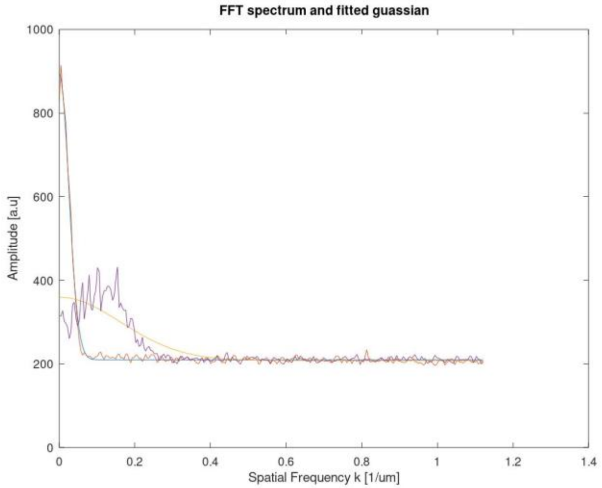






Well defined statistical means of stochastical surfaces #2





- Shape of structures
  - Can be estimated by 2D-FFT analysis
  - Axes of SEM analysis need to be aligned to FFT analysis
  - Shape of structures will directly influence ellipticity

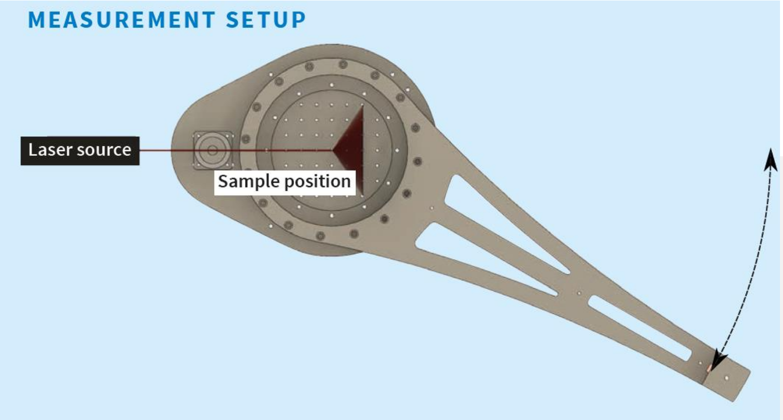
- A thought on the angular distribution
  - Interference lithography produces sinusoidal amplitude patterns
  - Stochastical superposition of sine terms (FFT synthesis) maintains sinusoidal shape
  - From central limit theorem it follows, that the angular distribution is connected to height and speckle size and will be **gaussian distributed**

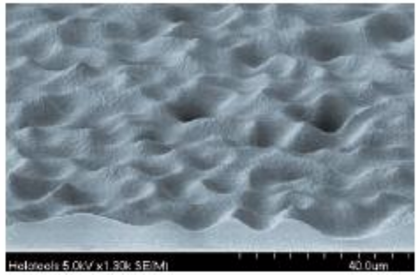
Connection between angular distribution and scatter angle will be discussed in more detail in the simulation chapter

Well defined statistical means of stochastical surfaces #3

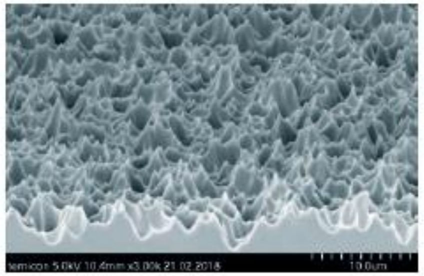
- Scattering angle
  - Combination of 2D-grainsize and depth-distribution leads to well defined scattering angle in two dimensions
  - Usually the scatter angle is highly non-Lambertian (for example an 20° x 40° elliptical diffuser)
  - Is measured by high resolution stepped detector with collimated illumination and a gaussian fitting routine

→ Stochastical surfaces can be precisely tuned to a desired scattering angle while controlling the grain size by interference lithography



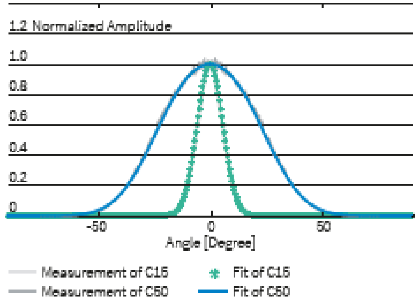


Gaussian circular
2D-stochastical surface

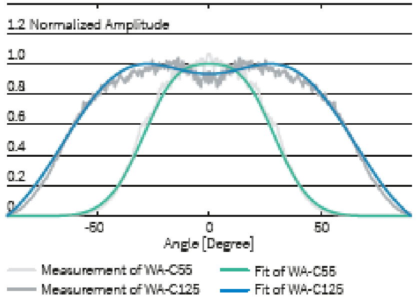


Wide angle circular
Surface with reduced grain size.

Gaussian circular



Wide angle circular



Optical properties and simulation approaches

Optical properties and simulation approaches

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- Surface structures cause redistribution of light
  - Refraction
  - Diffraction
  - Depending on feature size to wavelength ratio

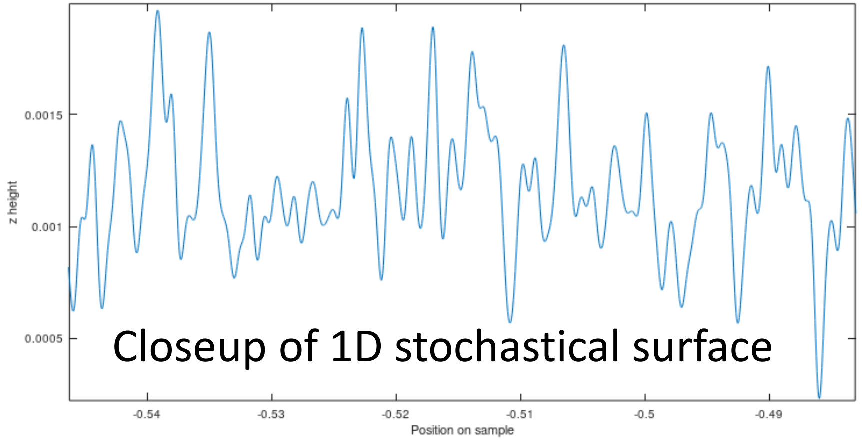
- Connection between surface properties and scattering of light
  - Shape of grains→ Ellipticity
  - Depth → Scatter angle
  - Grain size → Amount of haze / diffraction efficiency
  - Mind: Gaussian distribution of surface angles cannot be influenced and defines scatter pattern

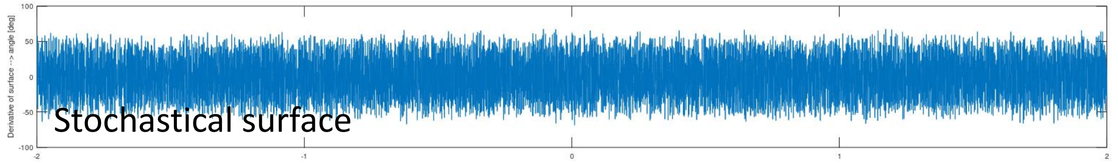
- Possible Simulation approaches with the goal of predictic scatter behaviour or speckle properties
  - Description based on surface angles
  - Ray Tracing
  - Huygens principle for speckle patterns

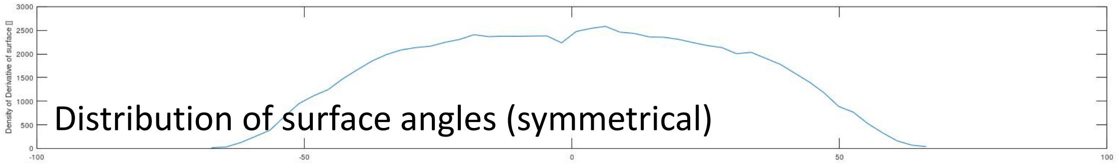
↓ Increasing complexity

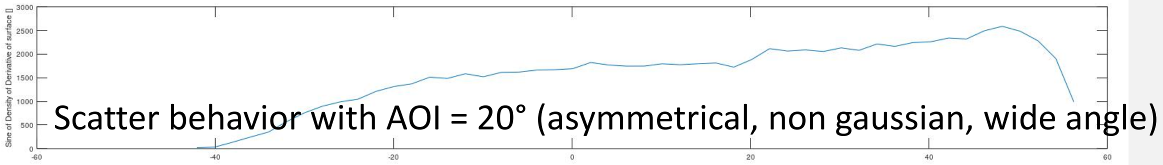
Optical properties and simulation approaches: Surface angle propagation

- Basic Idea (1D case)
  - » Tool for rough and fast estimation of scatter behavior
  - » Use distribution of surface angles and propagate light w.r.t. Snell‘s law
  - » Works for non gaussian distributions/surfaces as well
- Possible simulation results / possibilities
  - » 1st Order estimation of scatter angles with effects like tophat transitions
  - » Illuminated side structured or flat
- Challenges
  - » At the moment no proper validity check of results / range of applicability
  - » Fresnel losses (reflection, transmission) challenging
  - » TIR will become challenging
  - » Multiple reflections are not treated properly



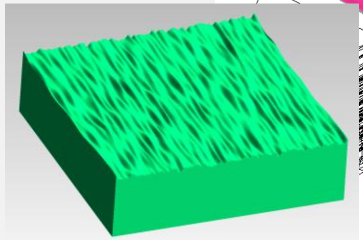






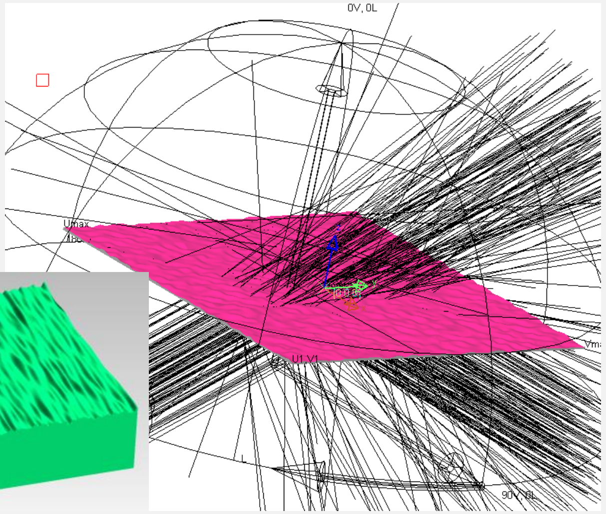
Optical properties and simulation approaches: Ray Tracing

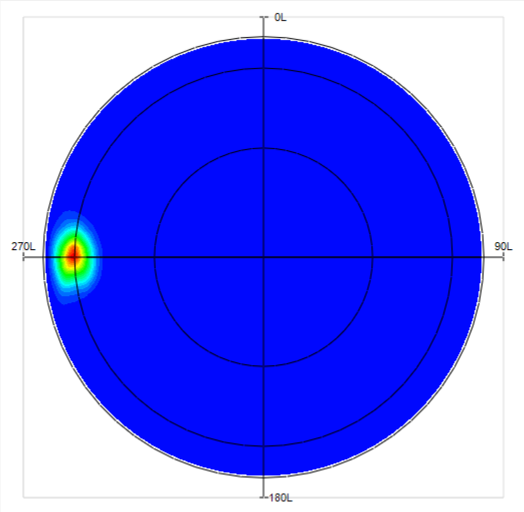
- Possible simulation results / possibilities
  - » Multiple interactions due to TIR*
  - » RTA** calculations
  - » BSDF simulations (**key** to efficient **upscaling** of simulation model)
  - » Oblique, non collimated input beams



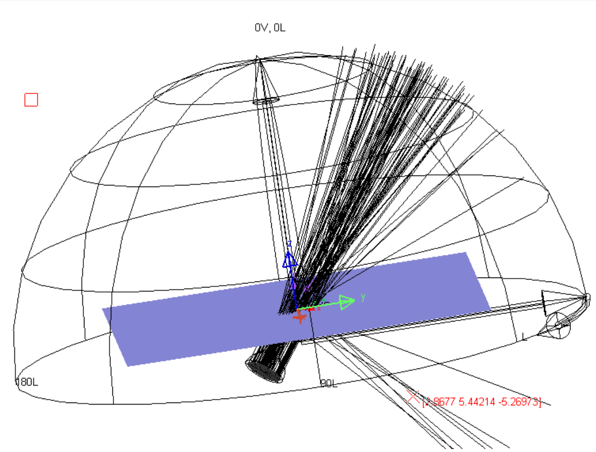
- Challenges
  - » High resolution mesh needed → Rather small areas are possible
  - » Computationally expensive, especially with increasing scatter angles (TIR causes high amount of trapped rays)
  - » System simulations or optimization not easily possible
  - » No diffraction effects included

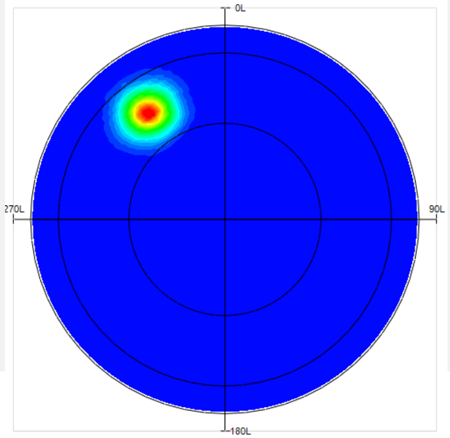
Simulation with realistically synthesized surface





Simulation with simulated BSDF Dataset (different AOI)

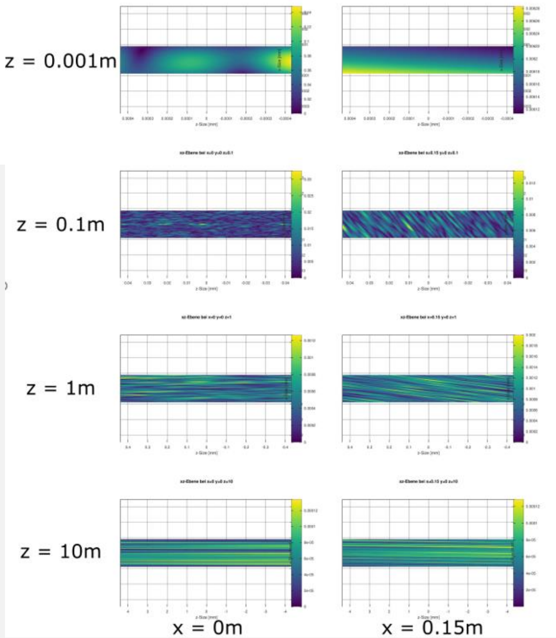




* Total internal reflection
** Reflection, transmission, absorption

Optical properties and simulation approaches: Huygens‘ Principle

- Idea
  - Summation of spherical waves of arbitrarily shifted phase
  - Geometrical setups of interference lithography is mimed
- Possible simulation results / possibilities
  - Speckle shape and size under varying illumination setups
  - Distortion of speckles due to oblique incidence
- Challenges
  - Microscopic interference pattern resulting from macroscopic setup must be simulated
  - Fine mesh of spherical waves needed → Influences size of simulated area (diffraction orders are self-similar)
  - Computationally expensive
  - Not suited for system simulations or scatter angles



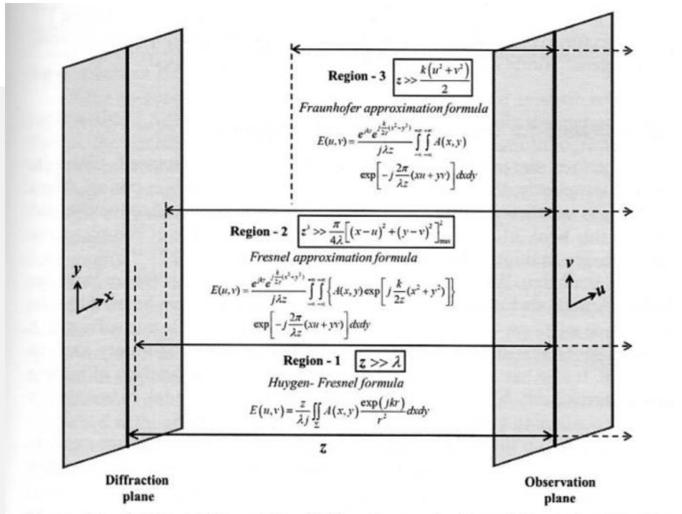
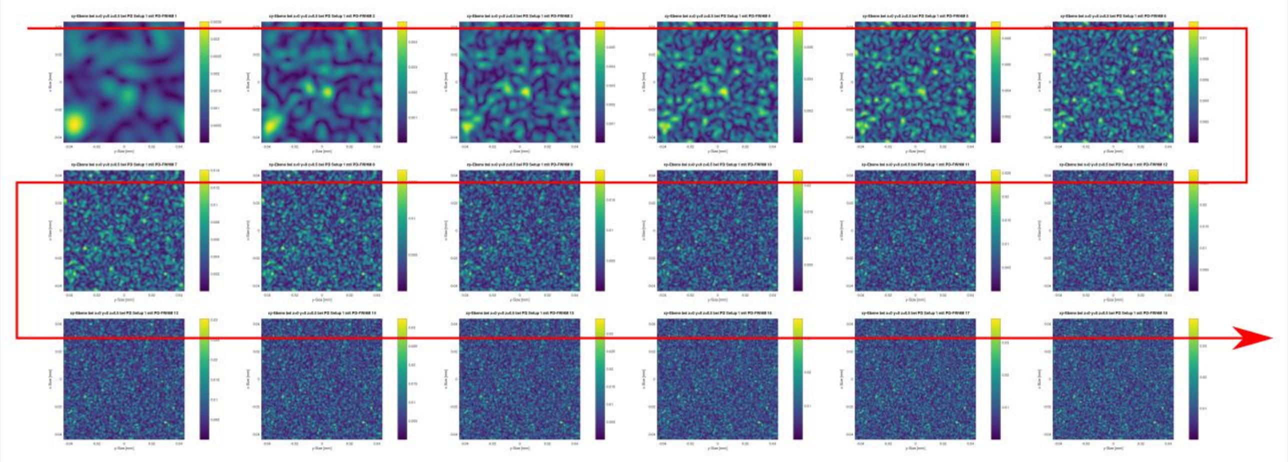


Figure 1.8 Depiction of the validity of different approximations of the scalar diffraction formula.

Distorted speckles due to oblique incidence



Change in grainsize due to change in illumination setup

Summary & Outlook

Summary

- Stochastical surfaces can be precisely tuned to yield gaussian scatter patterns from circular to pseudo-linear
- IL creates very high quality surfaces
- Surface properties can be measured and mathematically described by means of grainsize, depth, scatter pattern and surface angles
- Stochastical properties can be used to artificially create scalable and „clean“ random surfaces for simulation purposes
- Simulation can be done via various methods, depending on which property is asked
- Simulation of BSDF Files is possible, verification is needed

Outlook

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- Close the gap between ray-optical and wave-optical methods to answer remaining questions (for example diffraction efficiency)
- Investigate effects of varying materials and material combinations (TIR behavior, summation of scatter angles…)
- Understand interaction of diffusers with other optical devices better (for example display, sensing, lighting)
- Create simulated BSDF Files that match measured files with high precision
- Master transition to non gaussian scatter profiles like Tophat or Batwing distributions

Thank you!

Thank you for your patience, are there any questions?

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