Ghost Image Reduction in Lens Systems with Nano-Structured AR-Coatings Using CODE V, RSoft and LightTools

Outline

- **Overview**
- Initial Design, Image Simulation and Ghost Image Analysis
- Simulation of Diffraction for Detector Micro-Structure
- Monte Carlo Simulation of Ghost and Flare
- Subwavelength Nanostructured AR-Coatings
- Ghost Image Reduction with Subwavelength Structures
- Optimization of the Subwavelength Structure
- Conclusion

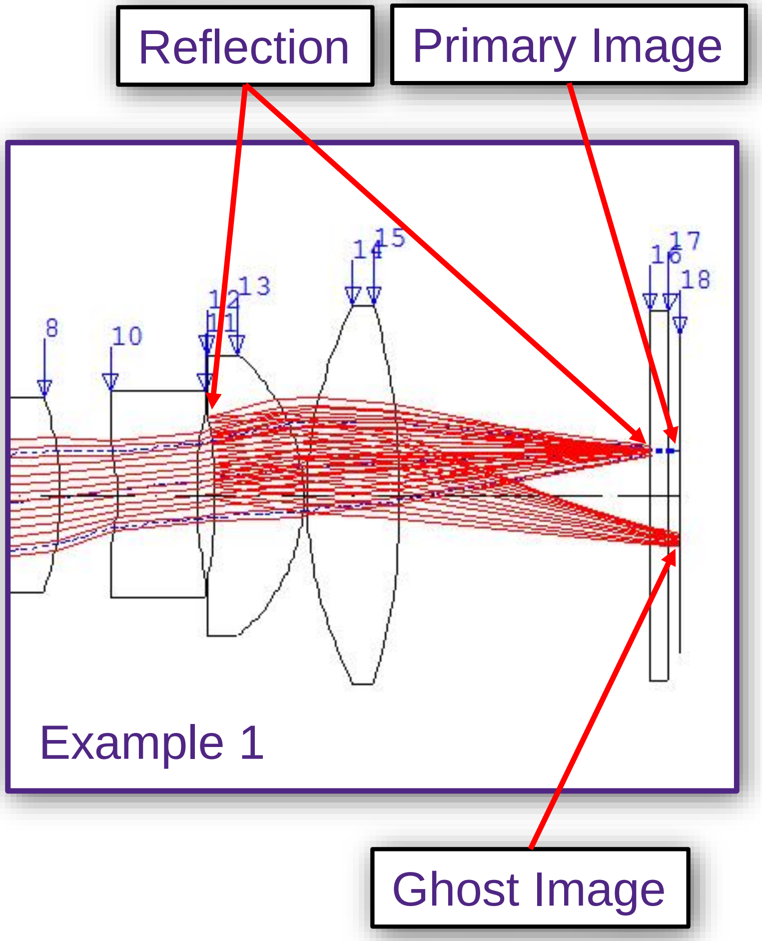
Overview

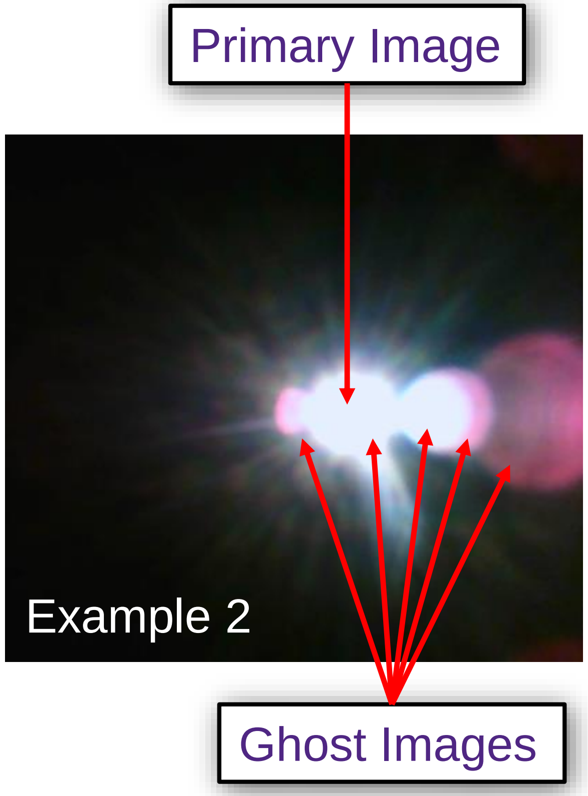
- The analysis and control of stray light, composed of ghost images and flare, is an important but complex task for the design of imaging systems
- Ghost images arise from multiple reflections off of surfaces in the primary optical path
  - Of specific concern are ghost images that impinge on the image plane at or near a focus
- Flare can arise from light reflecting off of lens mounts, non-optical surfaces of the lenses (such as flats and edges), and as a reflection off of the detector itself reimaged back onto the detector
  - Modelling light reflected off of the detector can be complicated by diffraction from the microstructure of the detector
- In this application note, we will discuss various computational approaches to simulating stray light in an imaging lens
  - All computation was done with Synopsys software, specifically CODE V, RSoft Device Tools, and LightTools

Ghost images in a cell phone camera image

Ghost Images

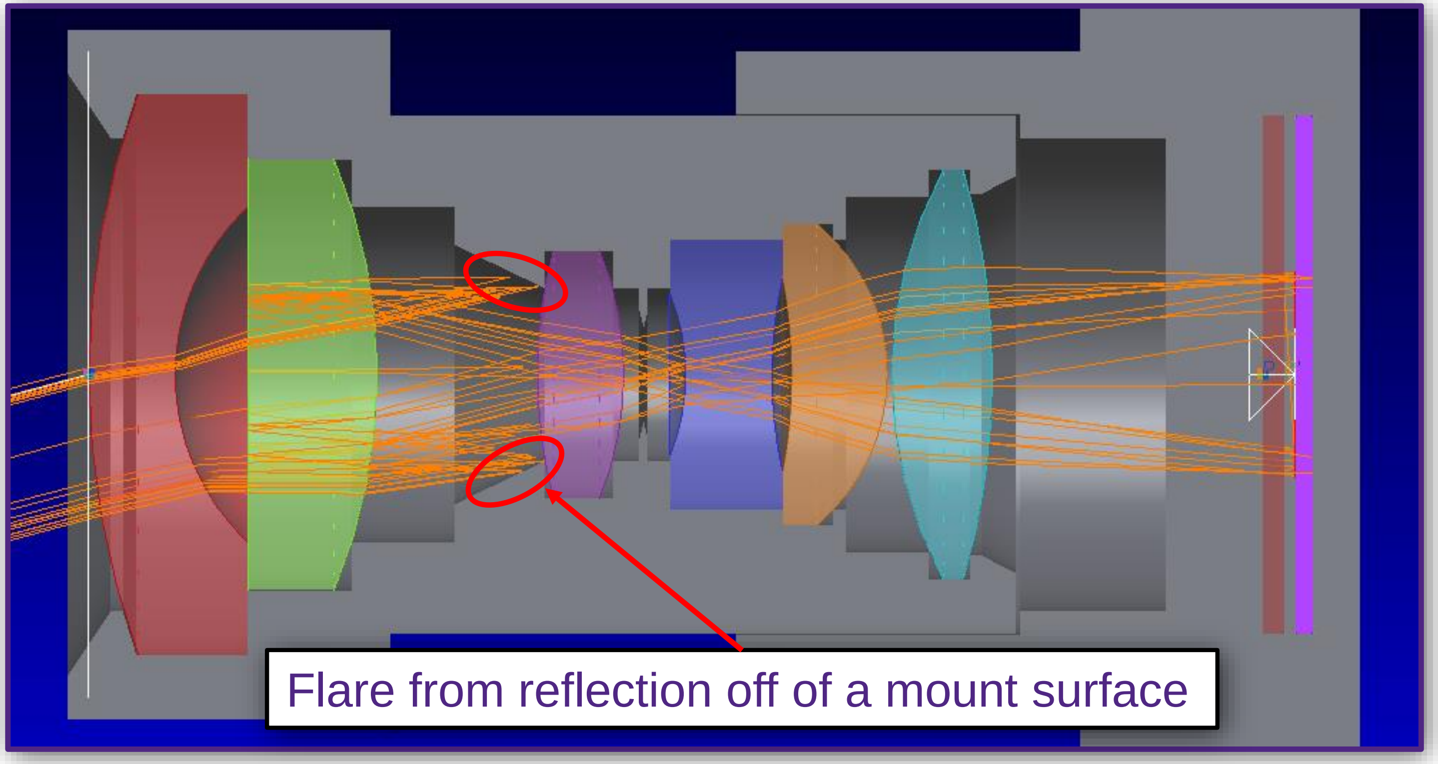
- Ghost images arise from reflections off of two surfaces in the primary optical path
  - Can include a reflection from the detector itself
- Light is then re-imaged back onto the image plane
  - If that light is near focus, then the resulting ghost image can be substantial
- Ghost images can typically be analyzed by sequential ray tracing software since the surfaces involved are from the main imaging path





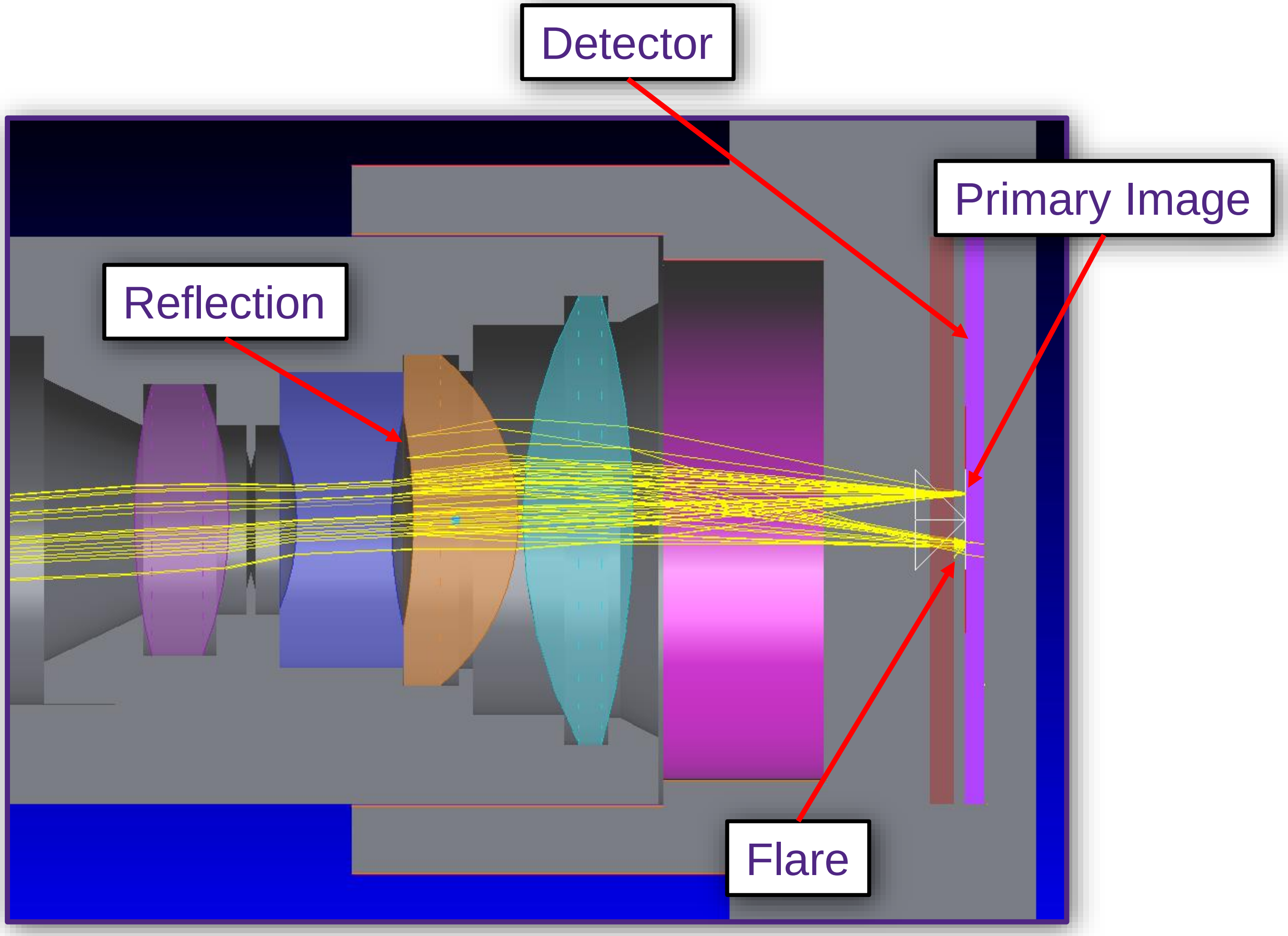
Flare from Non-Optical Surfaces

- Stray light can also arise from reflection or scattering off of non-optical path surfaces or simply passing through surfaces which are not part of the designed optical path
  - Referred to in this talk as 'flare'
- Possible surfaces that may give rise to flare:
  - Mount surfaces or baffling
  - Edge surfaces of lenses
  - Lens flats
  - Reflection off of the detector or off of surfaces surrounding the detector



Reflection off the Detector Structure

- The detector itself will reflect a portion of the incident light back into the lens
- This reflected light can, in turn, be scattered or reflected back on to the detector, causing ghost images or flare
- For solid-state detectors such as CMOS chips, the micro-structure of the detector can lead to significant diffraction patterns in the reflected light which may have an effect on the returning stray light pattern



Stray Light Workflow

- Shown below is a typical workflow for the analysis of stray light in a camera system when using Synopsys software

CODE V

- Design the lens to meet optical performance requirements
- Perform a ghost analysis to look for particularly difficult surface pairs
- If needed, re-optimize using @GHOST to control ghost images
- Export to LightTools for mount design and flare analysis

→

LightTools

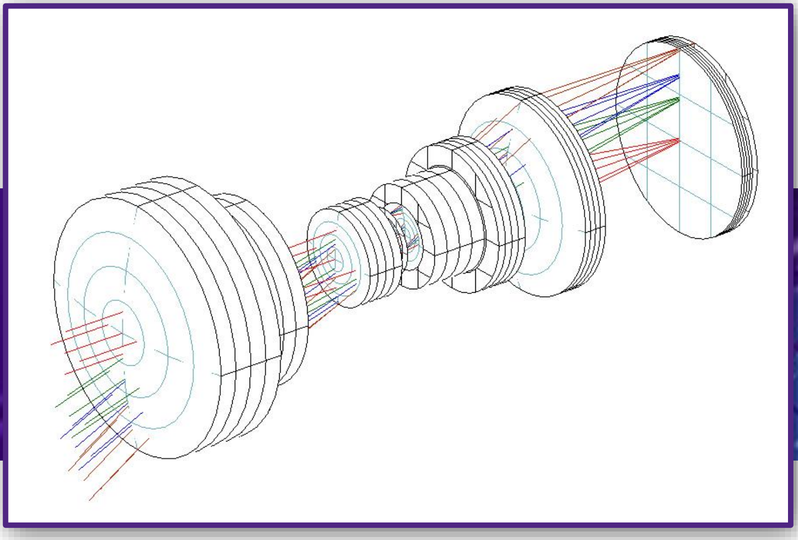
- Import the lens file from CODE V
- Design the lens mount
- Assign the optical properties to the surfaces of the mount, lens and detector
- Insert a source
- Run multiple Monte-Carlo simulations to analyze flare and ghost images

←

RSoft

- Model the detector chip and nanostructured AR-coatings in RSoft CAD
- Use the BSDF Utility to model the transmitted and reflected light of the structure using either FullWAVE or DifractMOD
- Export the BSDF file to LightTools

Outline



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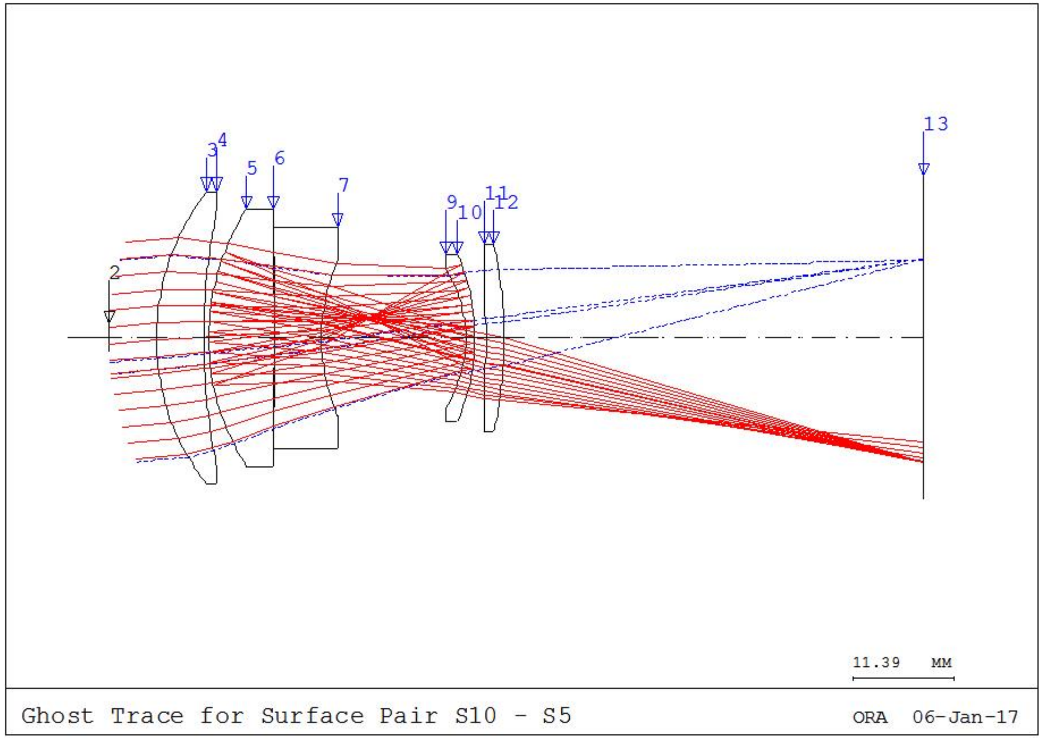
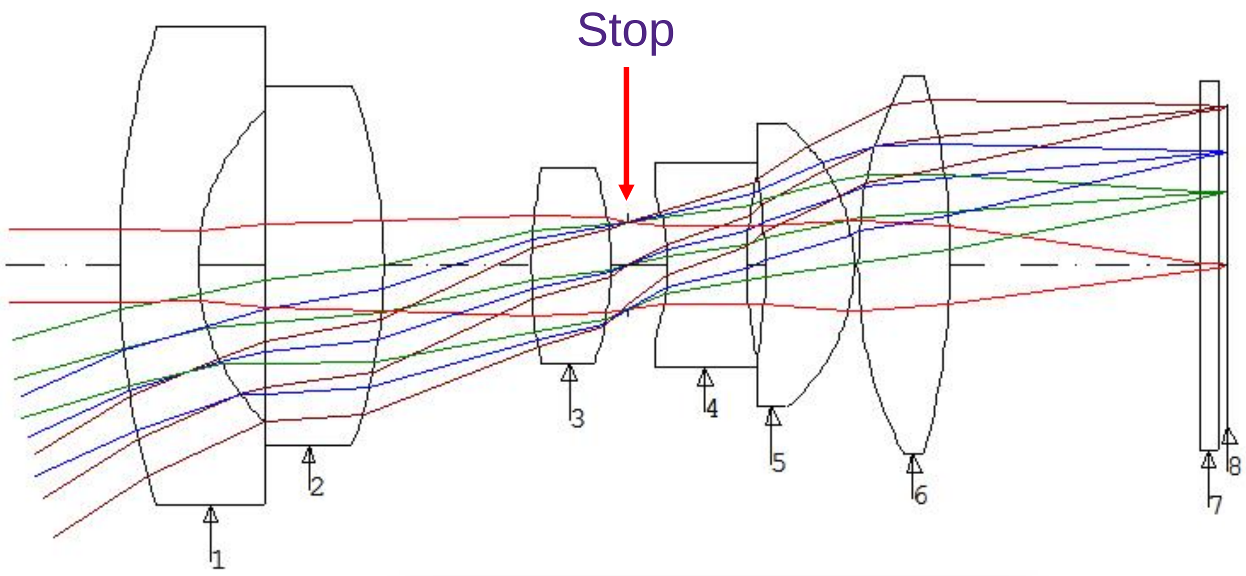
CODE V Stray Light Capabilities

- CODE V is a sequential ray trace code finely tuned for the design, optimization and analysis of imaging systems
- While CODE V does not have the ability to analyze flare which originates from non-imaging surfaces it does have three very powerful tools for analyzing ghost images
  - Ghost (**GHO**) analysis
  - ghost_view.seq macro
  - @GHOST function
- The first two features provide critical data in tabular and visual form on ghost images
  - The analysis is fast and allows the user to easily isolate troublesome pairs of surfaces for further analysis or optimization control
- The @GHOST function allows users to control for ghost image disk size during an optimization run
  - User specifies a surface pair to control



Lens Model

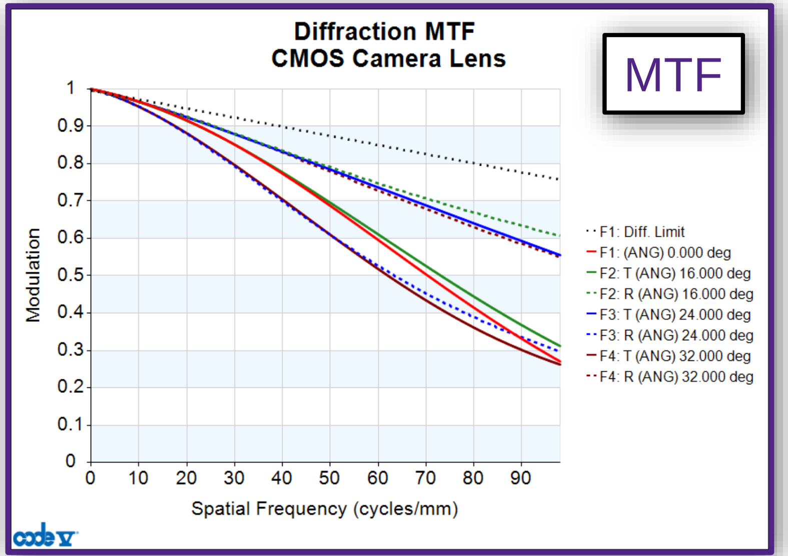
- For the purposes of illustrating the analysis of stray light we will use a moderately wide angle lens for a ½" CMOS detector
  - Number of Elements: 6
  - Focal Length: 6.4mm
  - Aperture: F/3.5
  - FOV: 32^{o} half-field at the corners
  - OAL: 27.75mm
  - Max Distortion: 0.41% (full field)
  - Relative Illumination: 74% (full field)
  - MTF: >25% @ 100 cycles/mm
  - Design Wavelengths: 656nm, 589nm, 434nm
  - Detector Size: 6.4mm x 4.8mm (1/2" Active Pixel Sensor CMOS)
  - Detector Pixels: 1280 x 960 (5µm x 5µm)



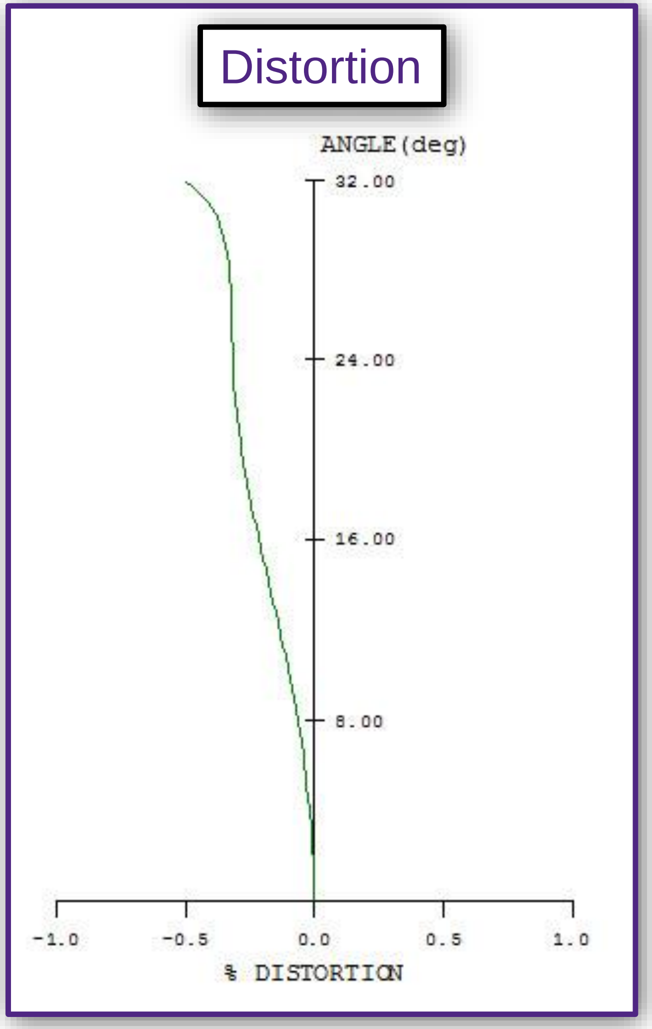
Elements 1 – 6: Lenses
Element 7: Cover Plate
Element 8: CMOS Detector

Critical Performance Measures

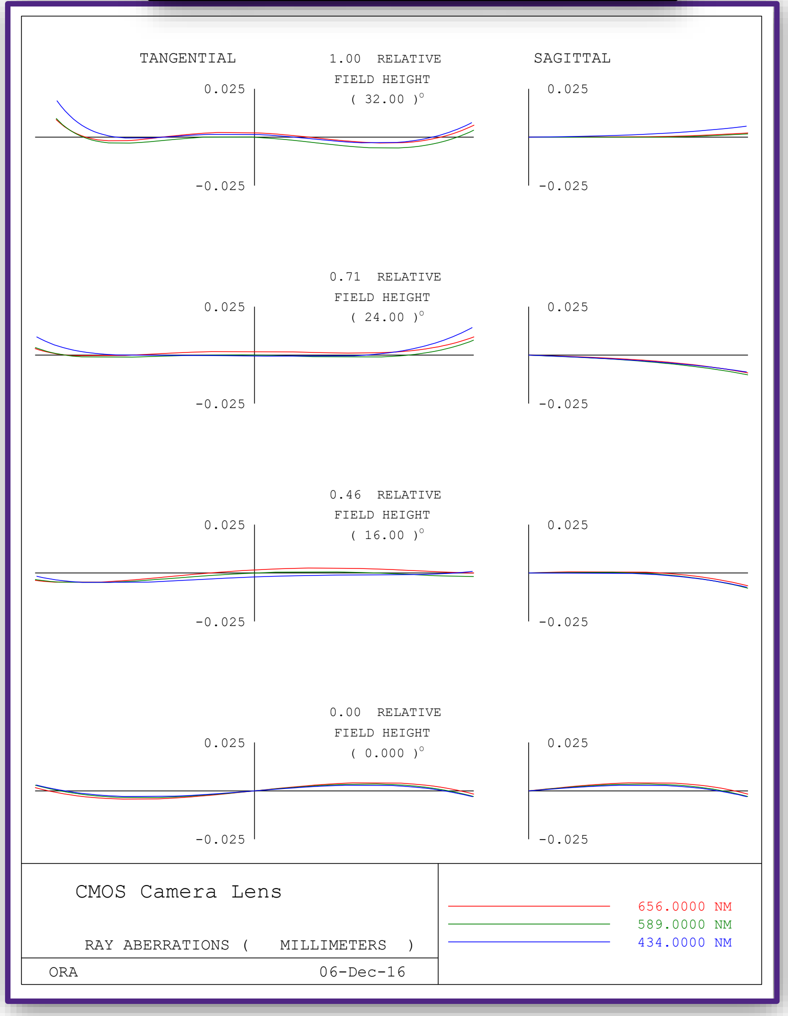
MTF

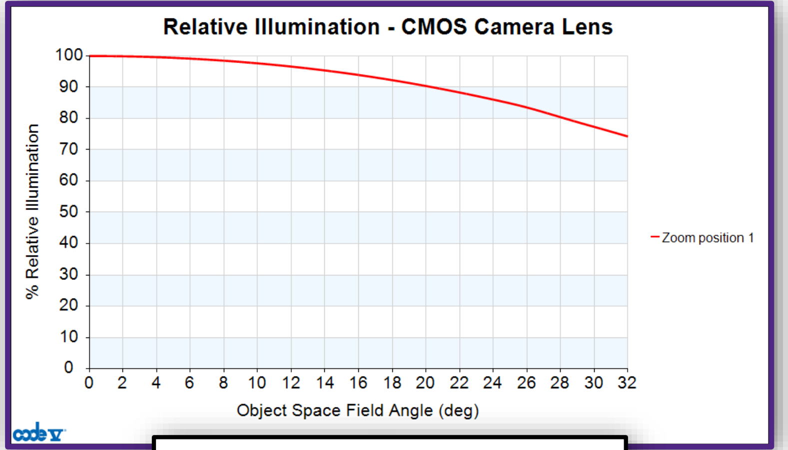


Distortion



Ray Aberration Curves





Relative Illuminance

Ghost Image Analysis

- The GHO option to lists image properties for double-reflections off of all surface pair combinations within the specified range
  – Data for GHO (and @GHOST) based on a first-order analysis for the on-axis field so accuracy may be limited for highly aspheric or off-axis systems
- Information listed include:
  – Surface Pair creating the reflection
  – Delta Back Focal Length (**DBFL**): Distance of the ghost image focus from the real image plane. Values near zero indicate a ghost image that focuses near the image plane
  – Effective Focal Length (**EFL**): This focal length value allows you to compute the size of the ghost image
  – Disc Semi-Diameter (**DISC**): Semi-diameter of the reflected beam at the real image plane
  – Pupil Ratio: Size of the ghost pupil to the stop. Values greater than 1 indicate that the ghost will be attenuated by the stop
  – Magnification: The size of the ghost image at its focal plane to that of the real image at the real image plane

Ghost Image Analysis

```
SSP  NO
SUR  S1..16
GO
    POSITION  1
NOMINAL BFL AND EFL  ----     0.326916     6.400000
```

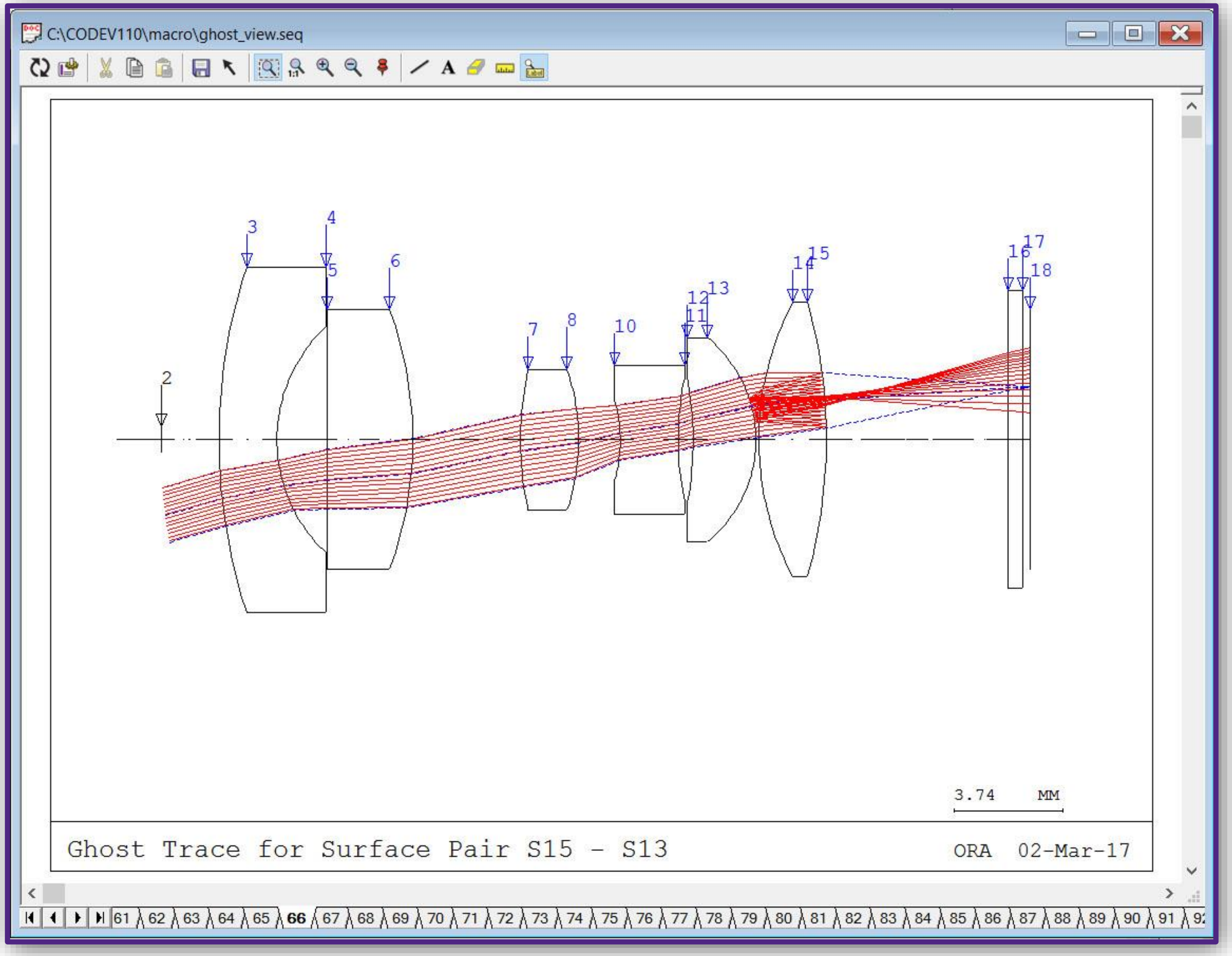
REFL 1	REFL 2	DBFL	EFL	DISC	PUPIL RATIO	MAGNIFICATION
2	1	4.057125	1.776985	2.087452	4.137500	0.277654
3	1	1.023653	3.491694	0.268039	1.897792	0.545577
4	1	8.712333	-6.109173	-1.303869	1.385792	-0.954558
5	1	0.389885	1.850262	0.192657	3.499439	0.289103
6	1	2.149228	-0.963007	-2.040492	7.160698	-0.150470
7	1	2.914373	-2.227296	-1.196325	3.178233	-0.348015
8	1	1.552137	-0.990676	-1.432452	6.816506	-0.154793
9	1	-0.830985	1.674430	-0.453741	3.692470	0.261630
10	1	-55.391567	82.172216	-0.616312	1.000000	12.839409
11	1	0.231609	-0.856658	-0.247189	7.514097	-0.133853

@GHOST:

- The @GHOST function allows access to any of the quantities computed by the GHO option (two reflection ghost image)
  - –This analysis is for the paraxial, on-axis field only
- Can be used to define a User Constraint in optimization to control the size of the ghost image from a specified surface pair
- The @GHOST function is very fast and easy to set up in AUT with good accuracy for spherical optics of moderate f/#s
- The principal drawback to using this option is that it is based on a paraxial ray trace on axis
  - –This means that it can loose accuracy (sometimes quickly) for non-spherical surfaces or fast optics

Ghost_View Macro

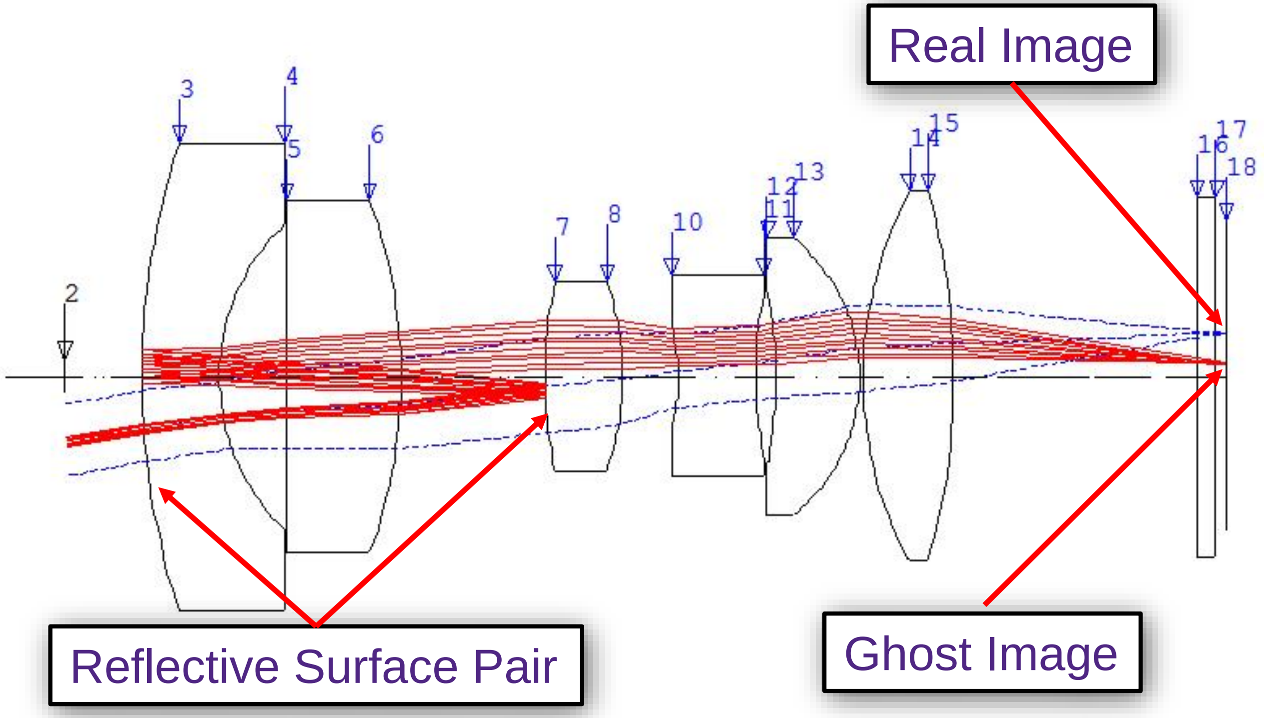
- The Ghost_View macro provides a visual representation for all ghost image surface pairs in the mode, allowing the user to quickly visualize the ghost image pairs
- The macro converts the lens into a non-sequential surface range allowing the rays to pass through the system multiple times
- Based on real ray trace data so it is accurate for off-axis and aspheric systems



GHO, Ghost_View example

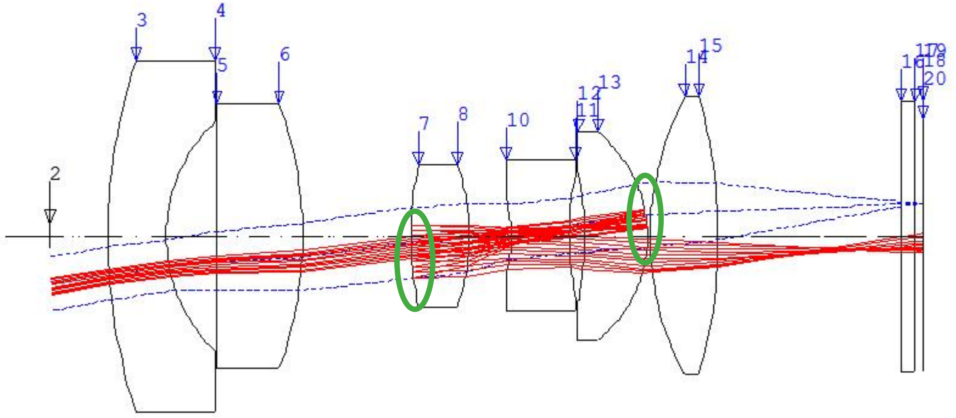
- In this example we see a ghost reflection pair of that might be of some concern
  - Reflection pair of surface 5 and surface 1
  - Note the small DBFL value indicating that the ghost image focus is very near the real image plane
  - Because of this, the DSC disc size is very small
  - On the positive size, the Pupil Magnification is significantly larger than 1 (~3.5 in this case) indicating that the ghost image is significantly vignetted

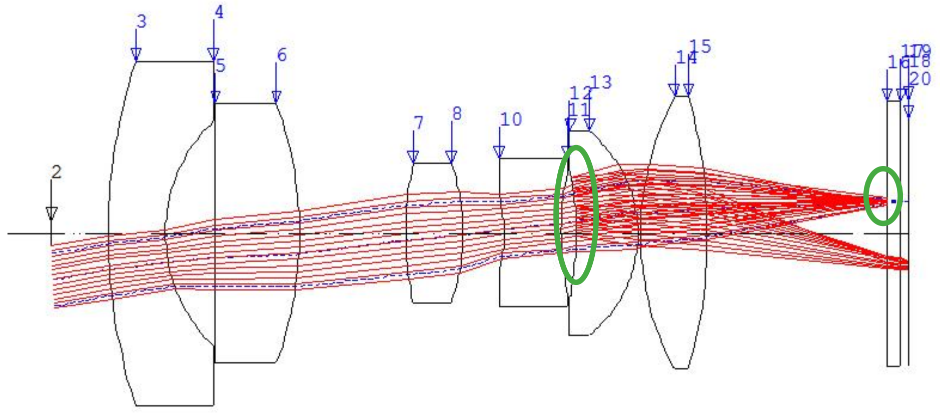
REFL 1	REFL 2	DBFL	EFL	DISC	PUPIL RATIO	MAGNIFICATION
2	1	4.057125	1.776985	2.087452	4.137500	0.277654
3	1	1.023653	3.491694	0.268039	1.897792	0.545577
4	1	[illegible]	-6.109173	[illegible]	[illegible]	-0.954558
5	1	0.389885	1.850262	0.192657	3.499439	0.289103
6	1	2.149228	-0.963007	-2.040492	7.160698	-0.150470
7	1	2.914373	-2.227296	-1.196325	3.178233	-0.348015

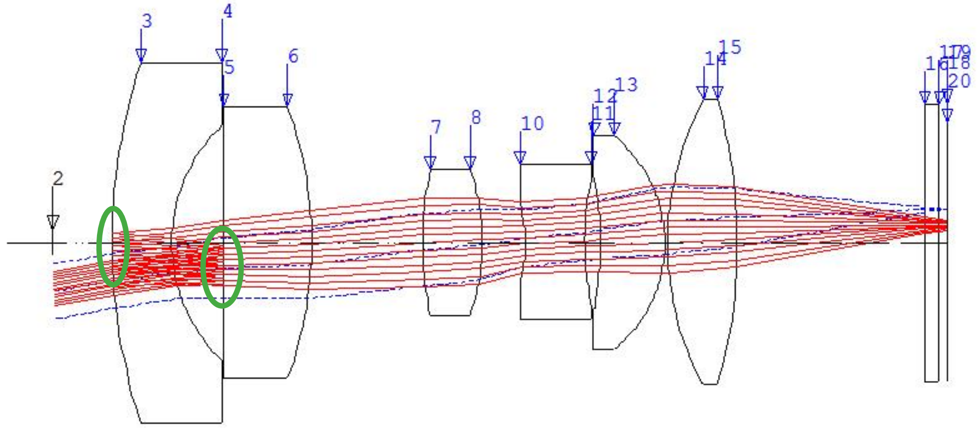


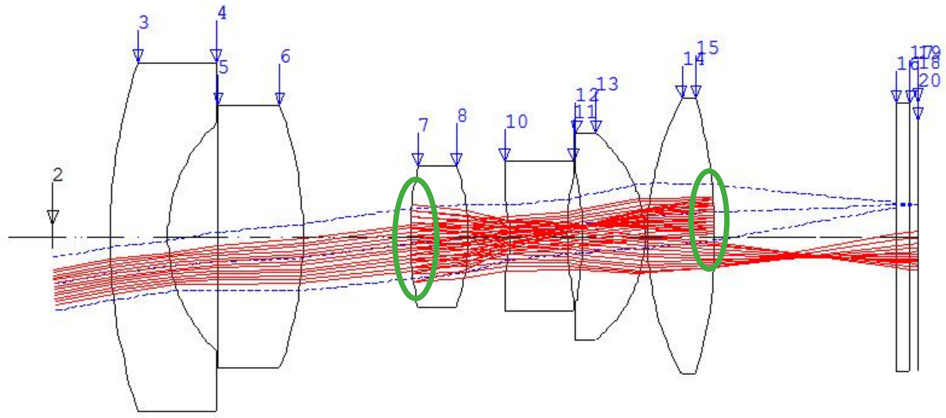
Ghost_View Output Examples at 10 Degrees

- Below are some examples of ghost reflections from a field angle of 10°





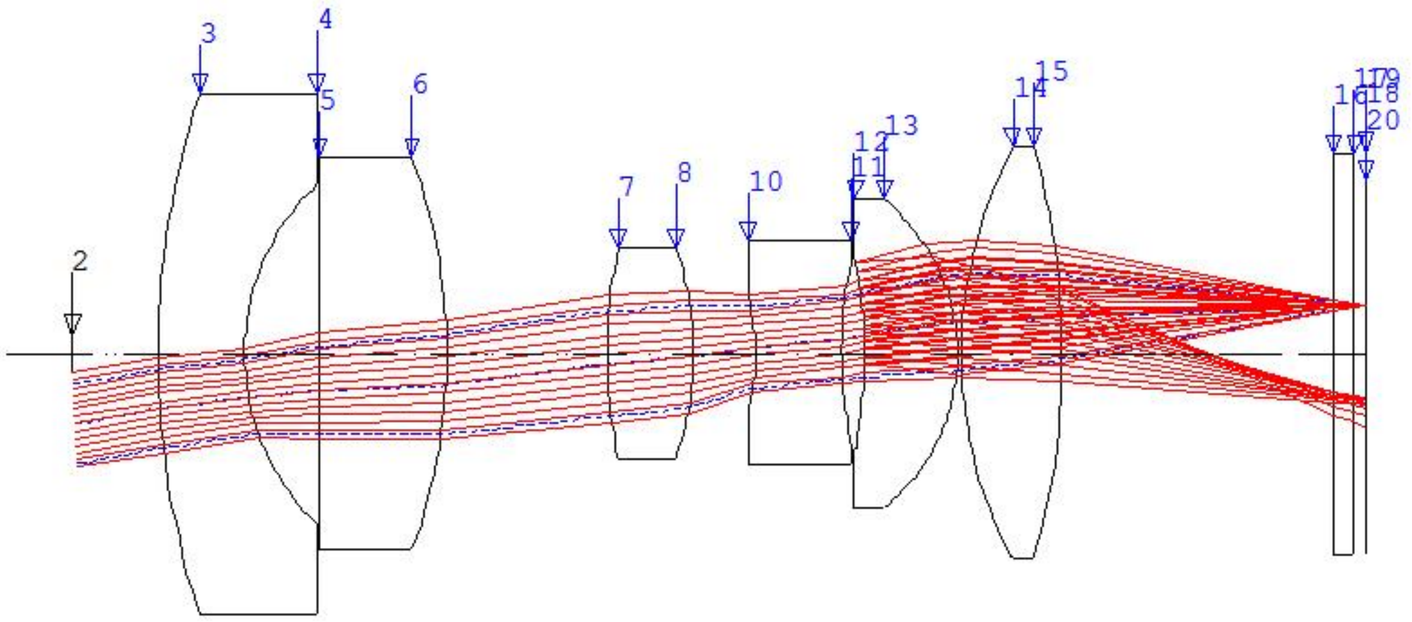




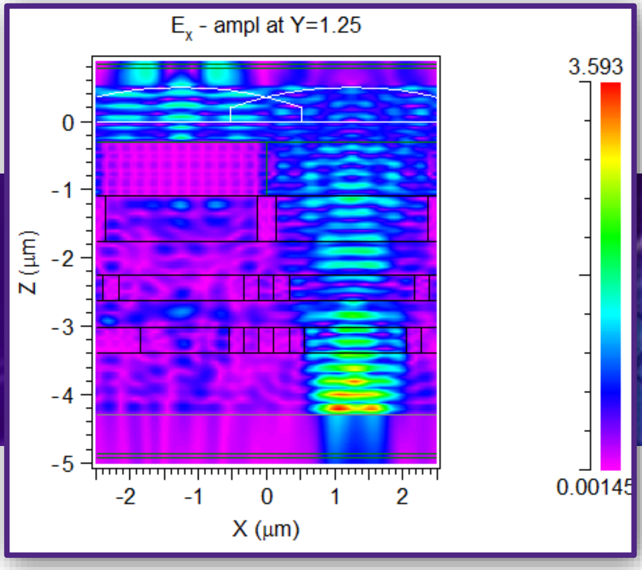
Including the Image Plane

- The detector itself can be a source of ghost images and is usually the main source of concern
  - Light reflecting off of the detector structure can be returned to the detector by lens surfaces
  - Reflectivity off of a detector is often much higher than a coated optical surface, in our case a full 36% reflectivity
- Only models the specular reflection and not any scattering off of the detector structure

Note that this surface combination, Surface 17 (detector) - Surface 12, is going to be of particular concern



Outline



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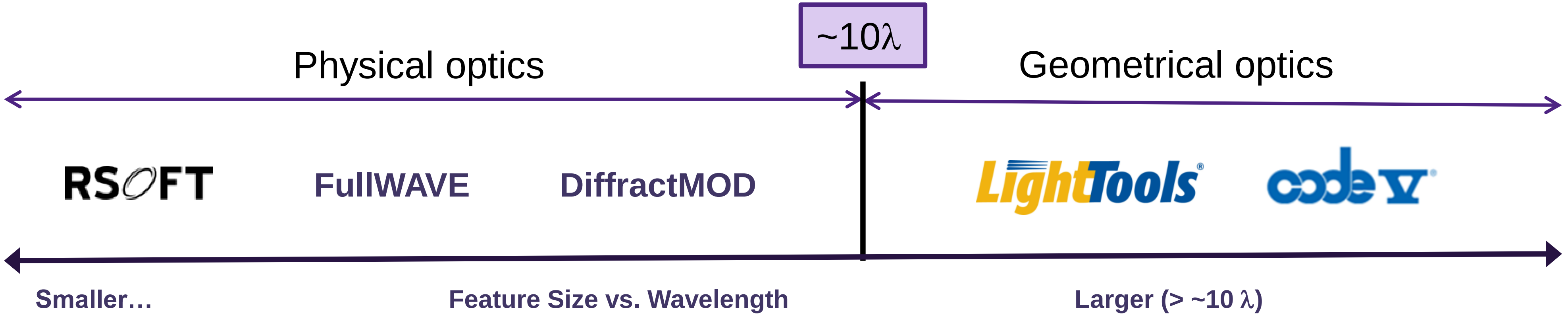
Simulating the Reflection Off the Detector

- One of the main concerns in stray light analysis for cameras that use solid state detectors is reflection off the detector surface itself
  - Light reflects off the detector structure and returns to the detector by a second reflection off another surface
- While the surface can be modeled as a specular reflector in CODE V or as a simple scattering surface using a native LightTools optical property, neither of these are an accurate representation of the reflected light
- The small scale of the detector structure creates diffraction patterns that cannot be accurately modeled using ray tracing alone
- By using either FullWAVE or BeamPROP, we can accurately model the pattern of reflected light from the detector structure and then export that information as a Bi-Directional Scatter Distribution Function (BSDF) file that LightTools can use with its ray trace
  - Makes use of the RSoft BSDF Utility

Combination of RSoft and CODE V-LightTools

- RSoft Component Tools
  - Based on physical optics
  - Maxwell's equations, etc.
  - Small photonics devices
  - Wave propagation and multi-physics
  - Diffraction, polarization, nonlinearity, electro-optical, thermo-optics, etc.

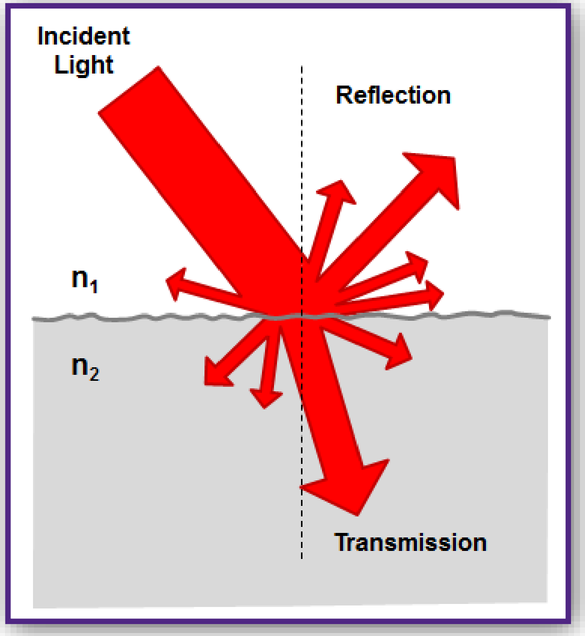
- LightTools and CODE V
  - Based on geometrical optics
  - Snell's law, etc.
  - Large bulk optical system
  - Ray tracing and beam propagation
  - Reflection, refraction, diffraction

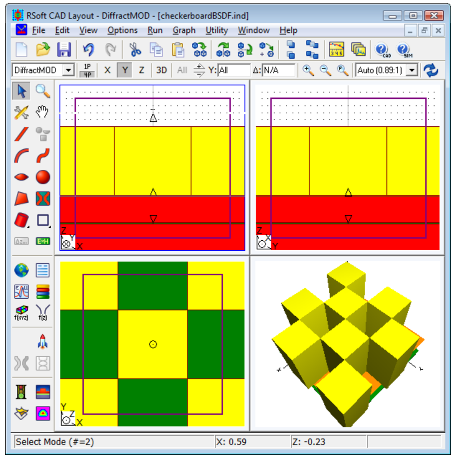


The RSoft-CODE V interface and BSDF RSoft-LightTools interface allow users to combine RSoft and CODE V and LightTools to design a large image or display system with nanostructures

LightTools BSDF Interface

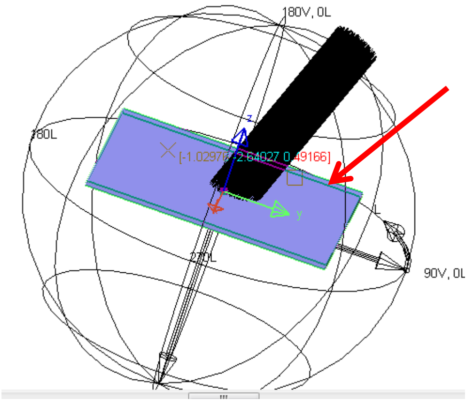
- BSDF files contain information about how a surface or structure scatters light (both reflection and transmission)
- Scatter information is stored as a function of angles, wavelength, and polarization
- BSDF data for both the thin film stack and the patterned surface can be calculated by FullWAVE or DiffractMOD





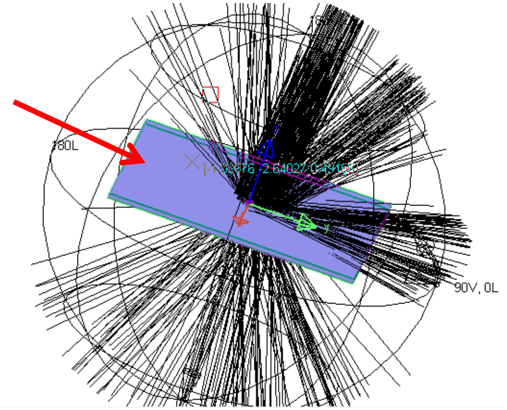
Periodic Nano-structure

- Simulations results are needed at a range of input angles, wavelength, and polarization
- Reflection and transmission results are combined into single BSDF file
- This file is then exported to LightTools and applied as a surface property



Light incident on BSDF surface

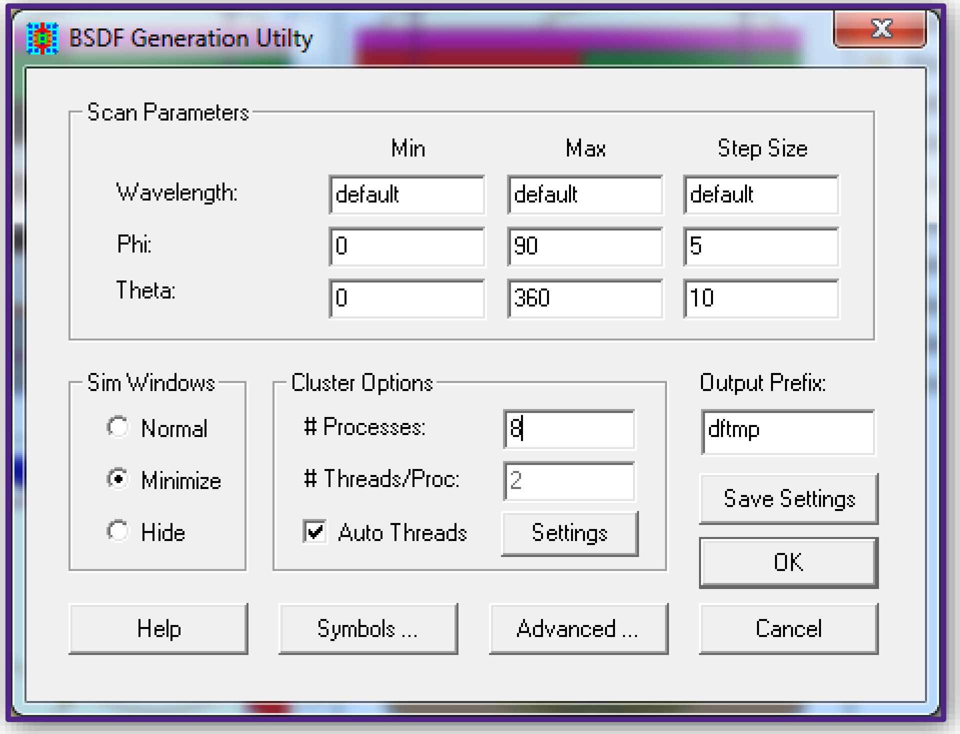
BSDF Surface

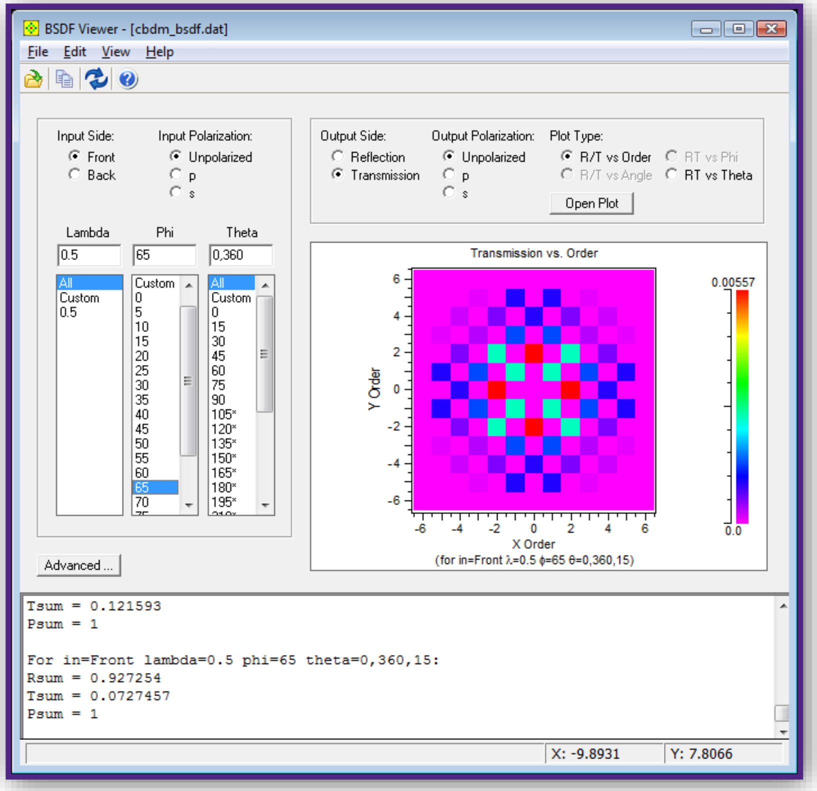


Scattering from BSDF surface

LightTools BSDF Interface

- To automate the process, the RSoft tools feature the BSDF Utility, which automates the BSDF calculation over a range of incident angles, wavelengths and/or polarization
- A viewer is available to visualize the BSDF results before they are exported to LightTools

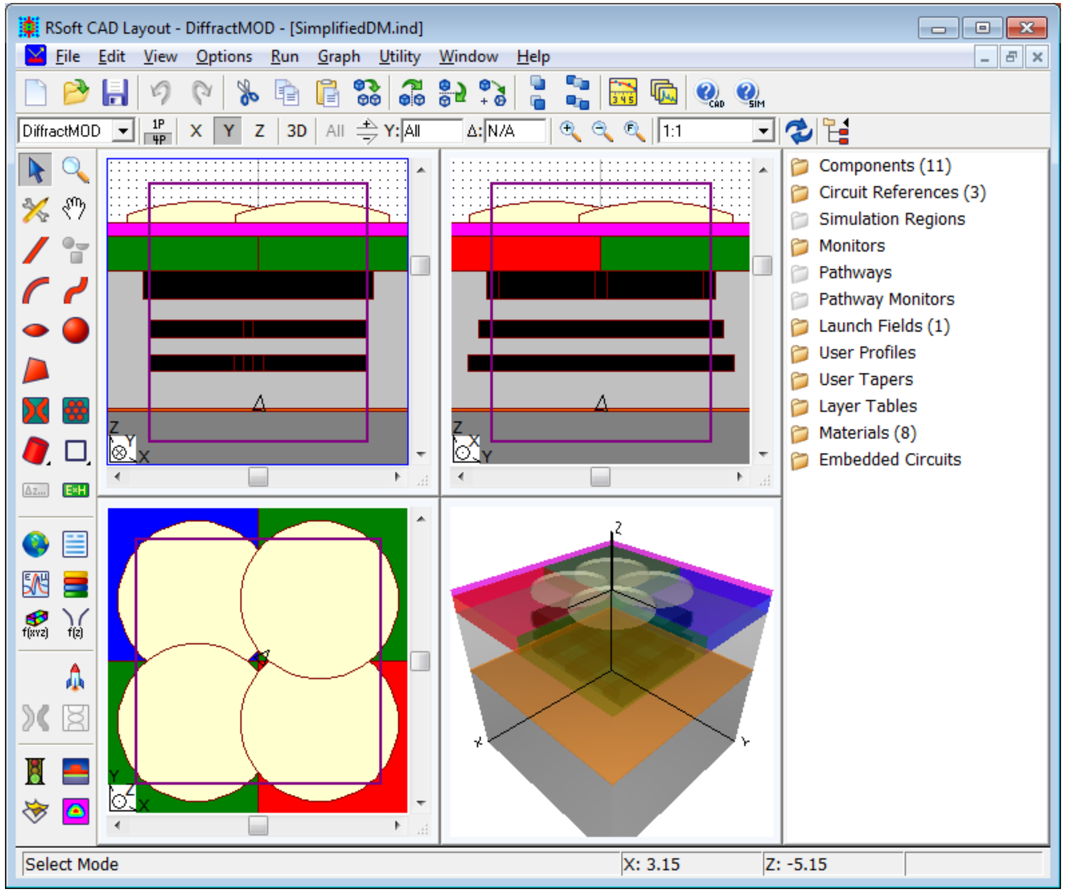




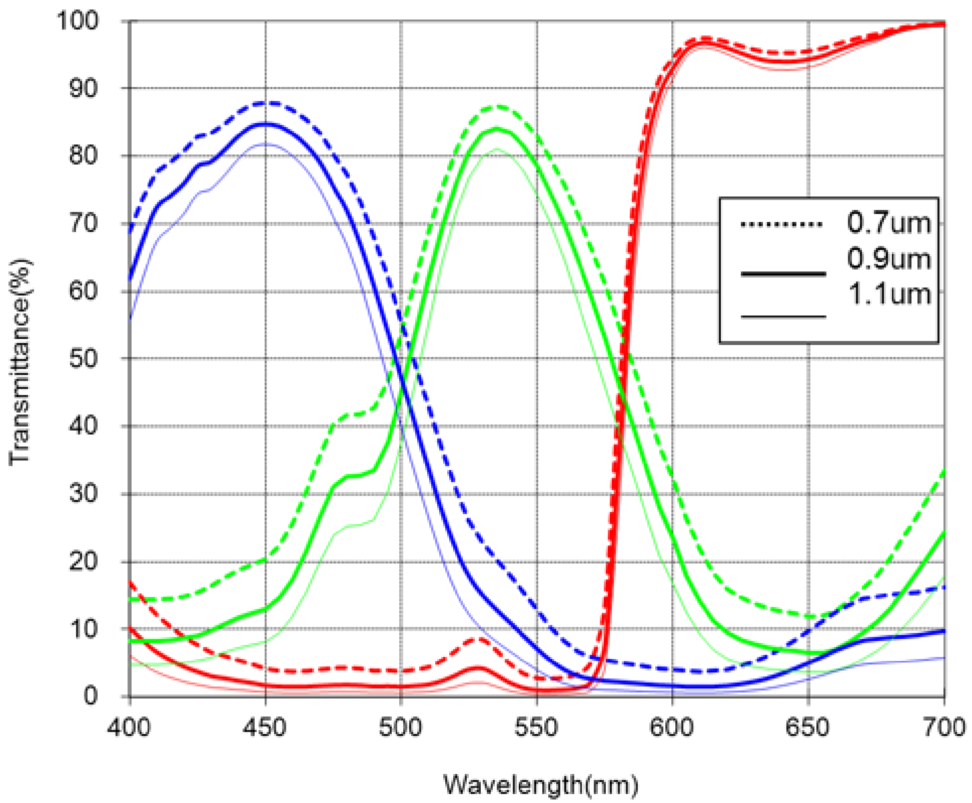
CMOS Image Sensor

Geometry and materials

- Simplified version of a real device, with 4 sub-cells, 1 blue, 1 red and 2 green



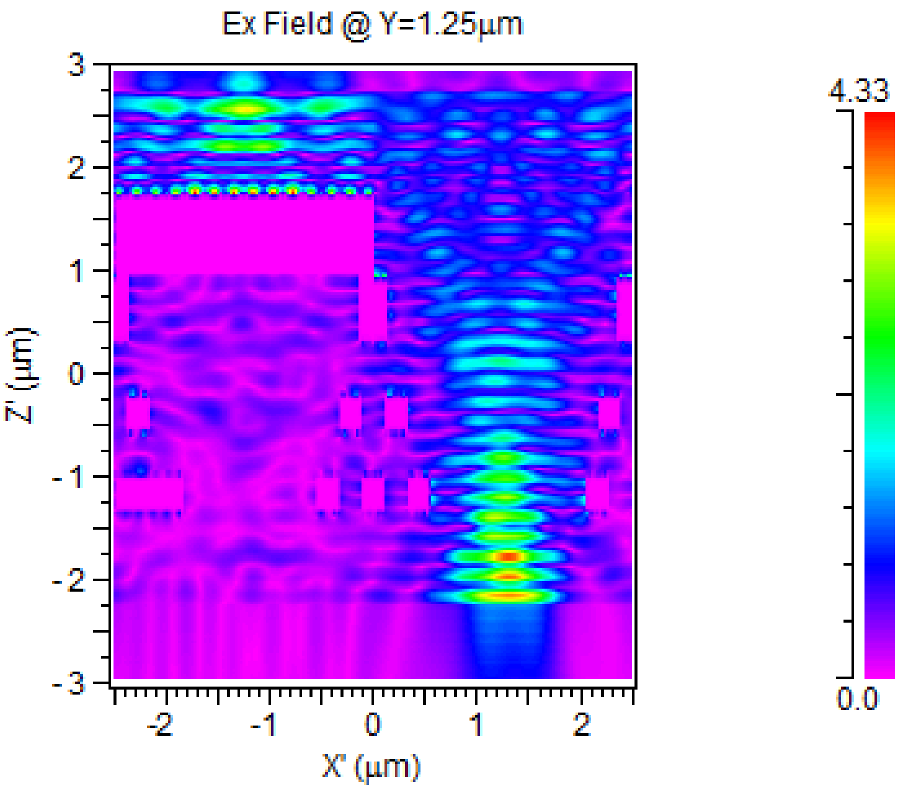
- Material properties of color filters are fitted based on transmission spectrum of Fujifilm's COLOR MOSAIC



Comparing FullWAVE with DiffractMOD

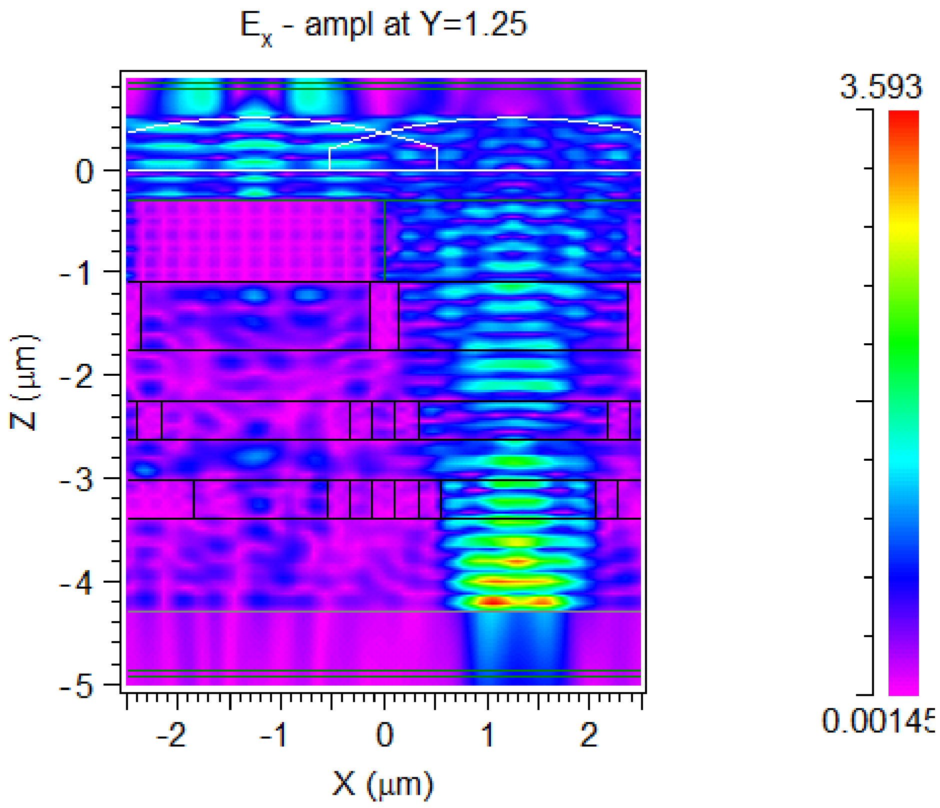
- FullWAVE
  - 5.2G RAM and 32 minutes on 16-cores

    5 hours on 1-core



- DiffractMOD
  - 1.6G RAM and 1.5 minutes on 16-cores

    3.8 minutes on 1-core

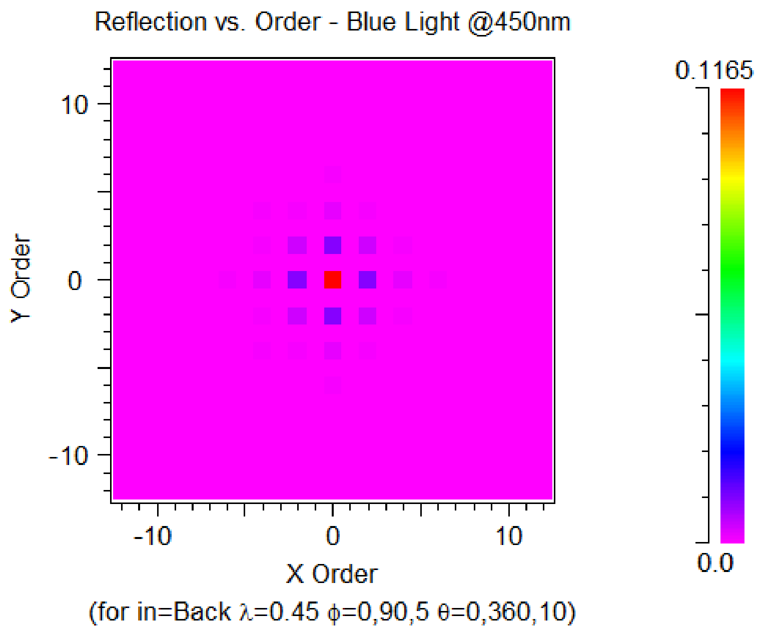


DiffractMOD is more efficient, especially for BSDF calculation with many simulations

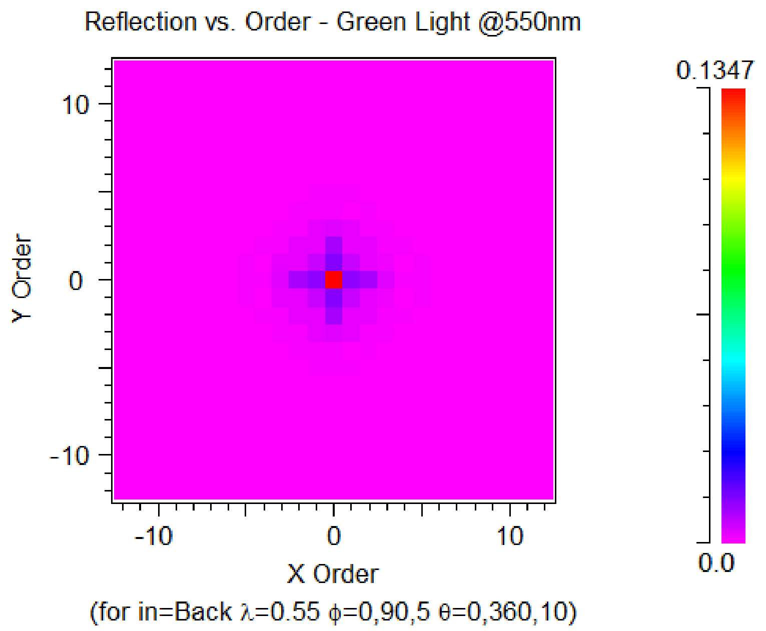
Reflected Diffraction Pattern by Wavelength

- Here we see reflected intensity results expressed in terms of diffraction orders for three different wavelengths

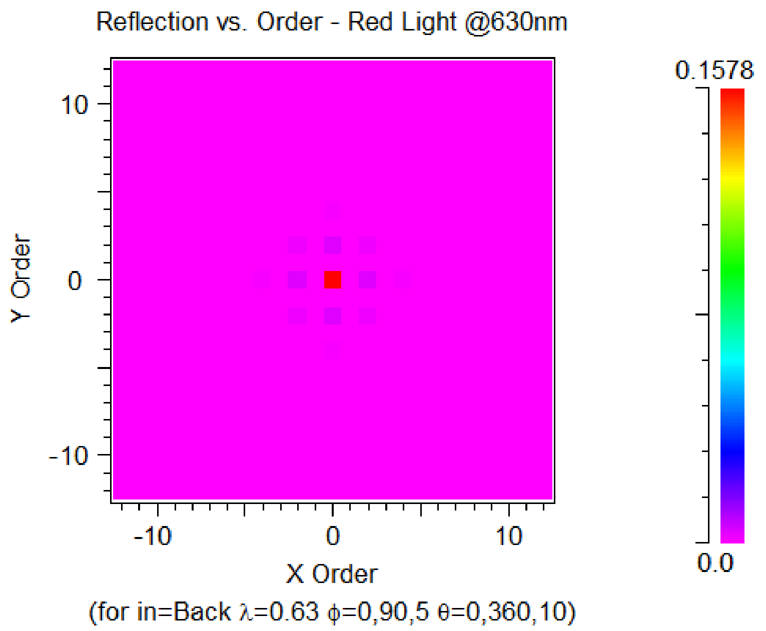
Blue



Green

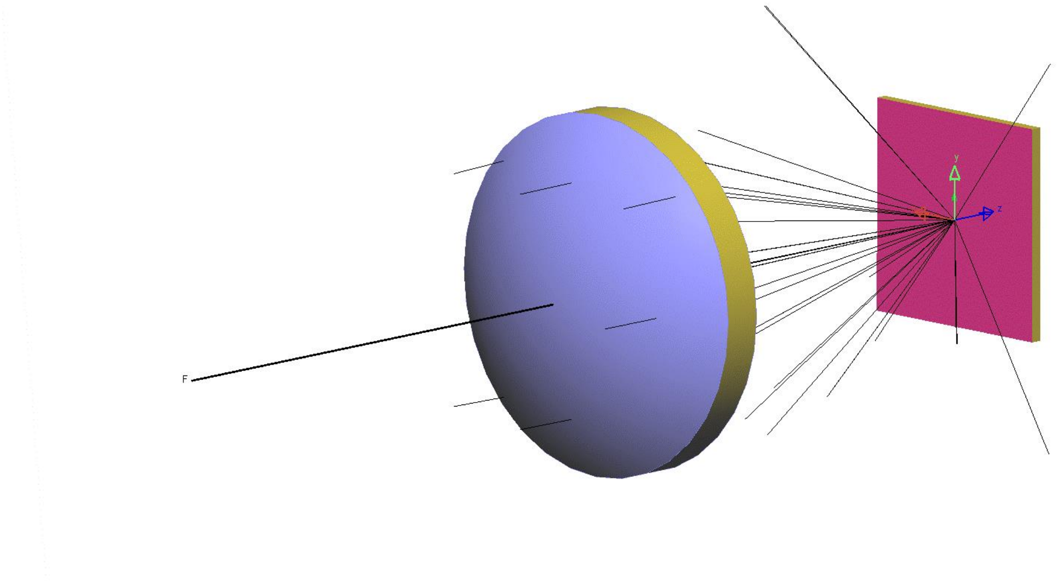


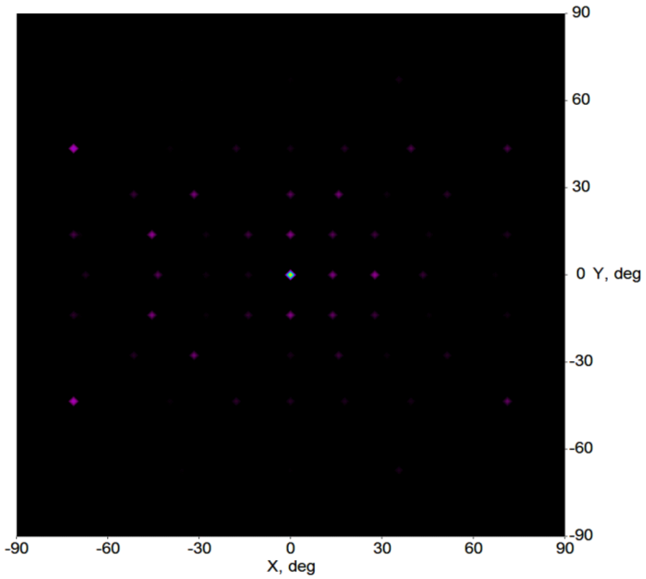
Red



Reflected Diffraction Pattern Shown in LightTools

- Here we see the reflected intensity pattern from the CMOS chip at 550nm as seen in LightTools for various input cone angles
- The charts are scaled independently in order to see the results more clearly





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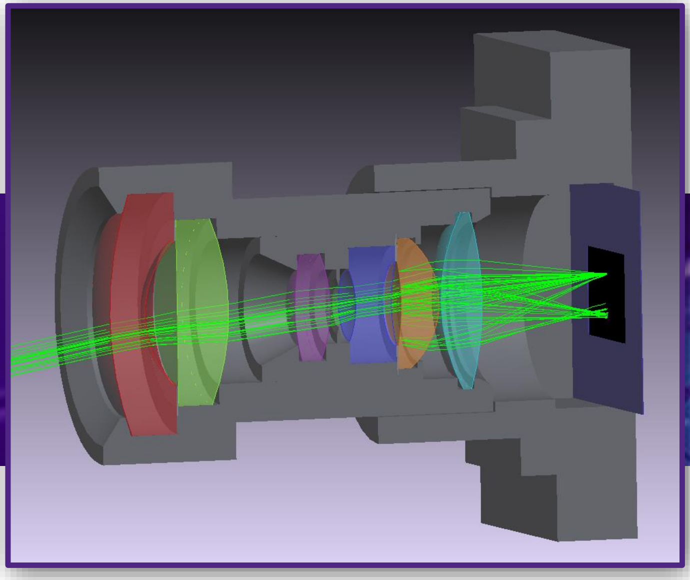

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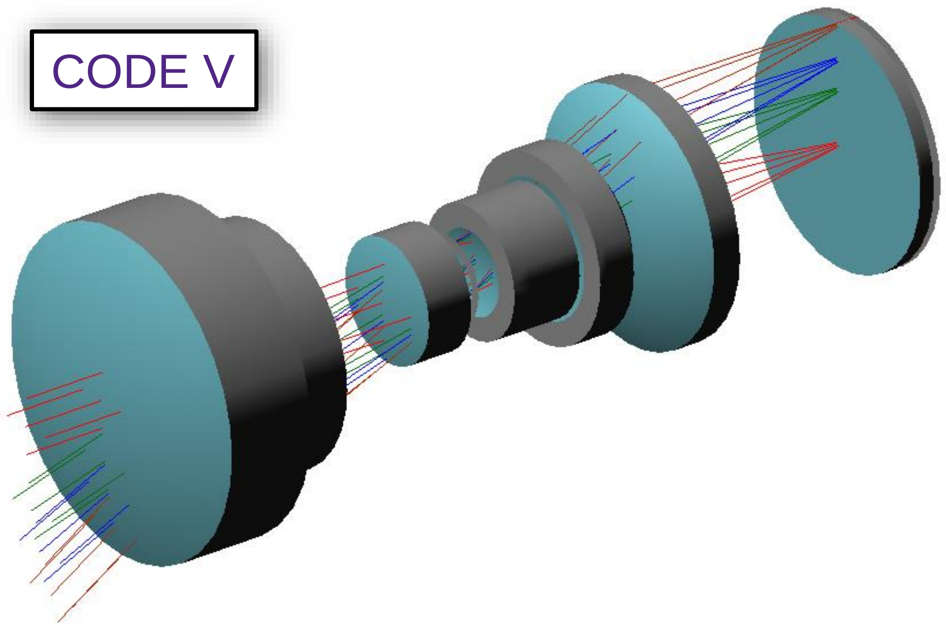
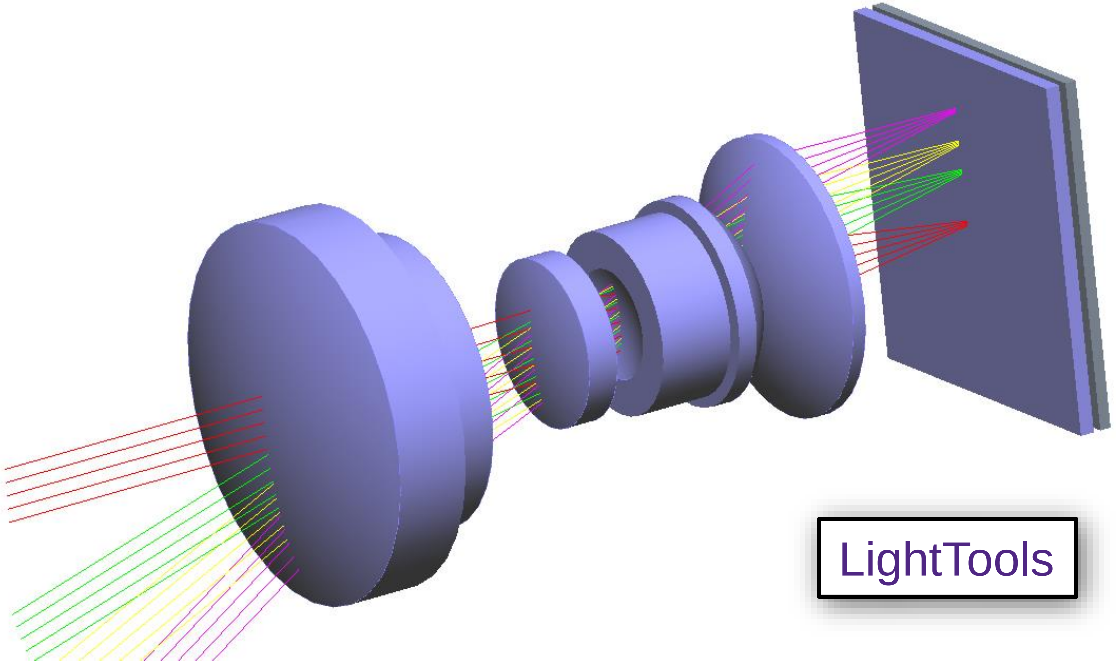
LightTools Stray Light Capabilities

- LightTools is a non-sequential ray trace code intended for the design, optimization and analysis of illumination systems
- Users can easily add lens mounts and other structural elements to the lens model by constructing them directly or by importing them from CAD
- LightTools uses a Monte Carlo ray trace approach to simulation the flow of light
  - Millions of rays can be traced through the lens and the results are collected on the detector(s)
  - Optical properties can be set to split light at ray surfaces so that reflected and transmitted light can be modeled
- The results generally take more time to simulate that in CODE V and are more complex to analyze
- For this purpose, LightTools features several primary tools for analyzing stray light
  - Region analysis
  - Ray Path and Ray Path Analyzer
  - Receiver filters

Importing the Lens from CODE V

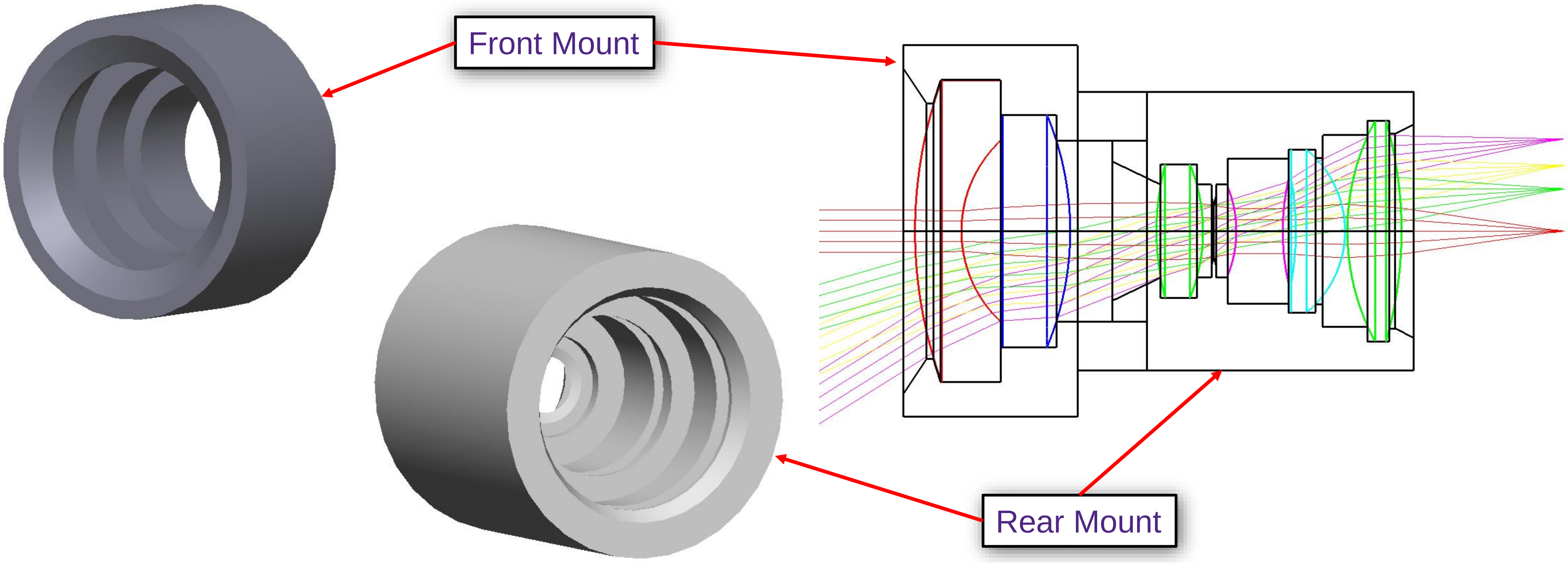
- For our example, the lens system was imported from CODE V into LightTools using CODE V's LightTools Export feature
- The exported lenses were sized according to the edge or clear apertures defined in CODE V
- Lens sizes were then adjusted in LightTools to match physical part sizes





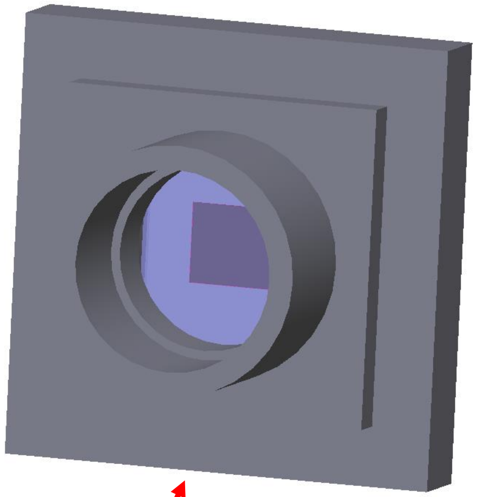
Lens Mount

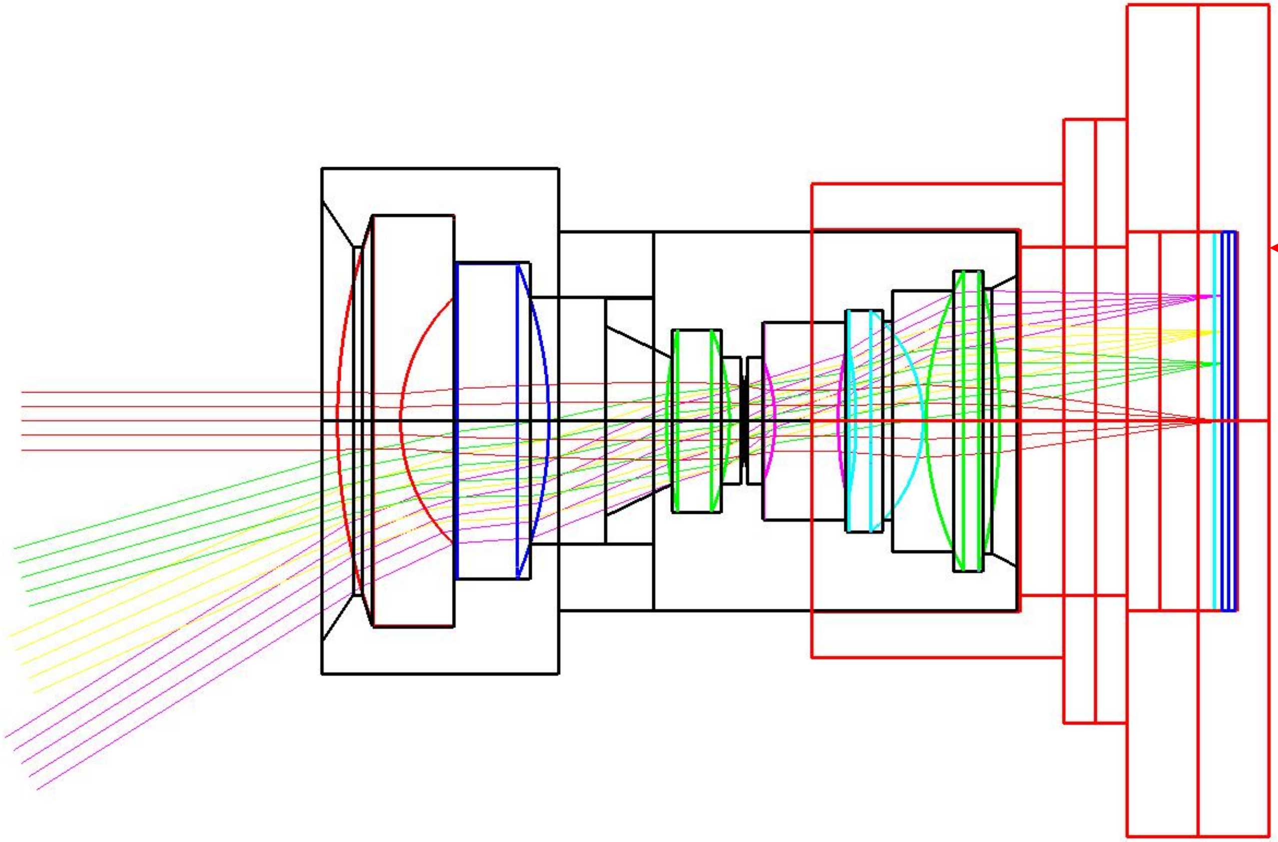
- The lens mount was created in two parts using native LightTools geometry
  - –It would also be possible to import this mount hardware from a CAD package

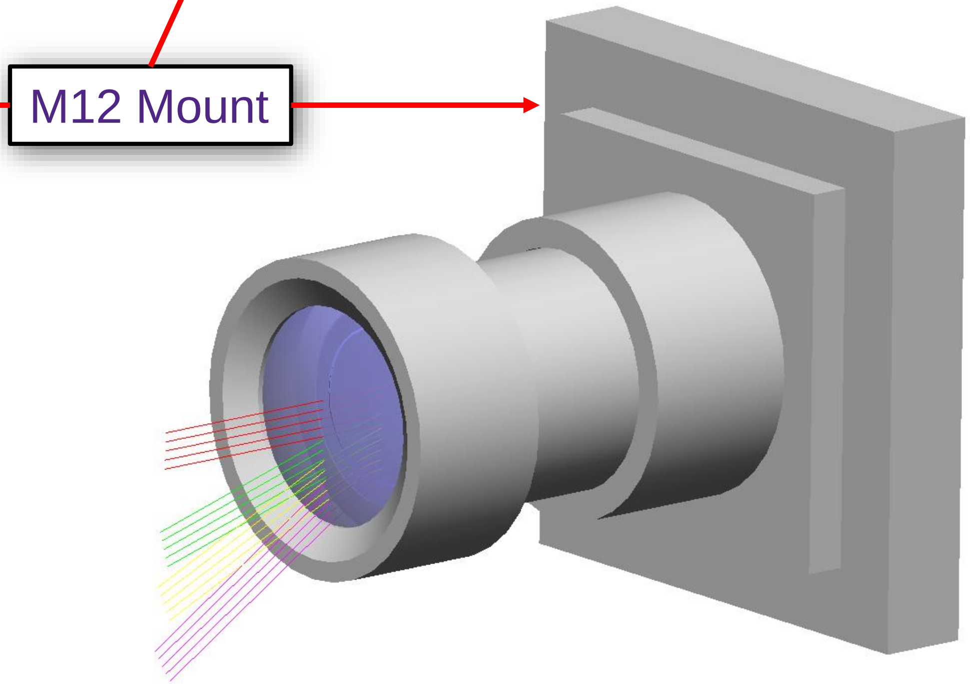


M12 Detector Casing

- A M12 mount with a detector casing, detector and cover plate were also added to the model





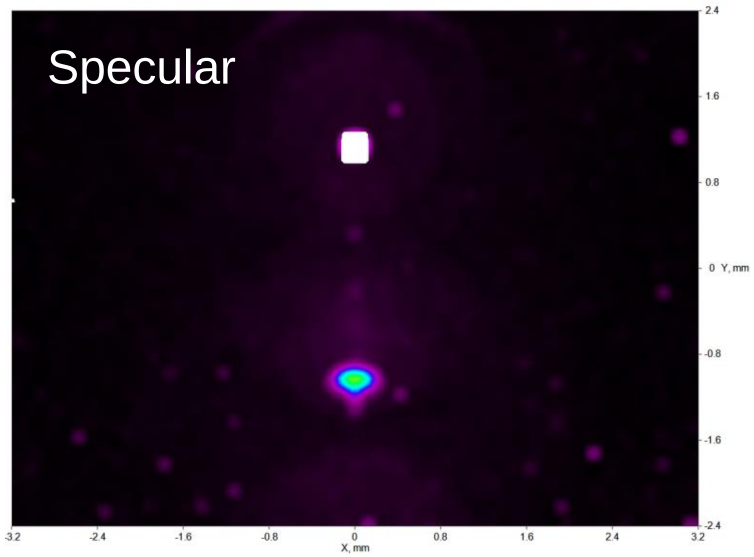


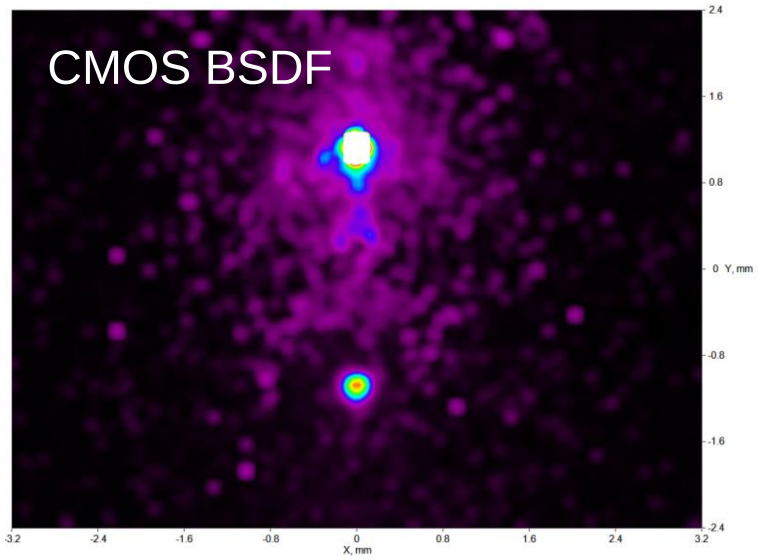
Optical Property Definitions

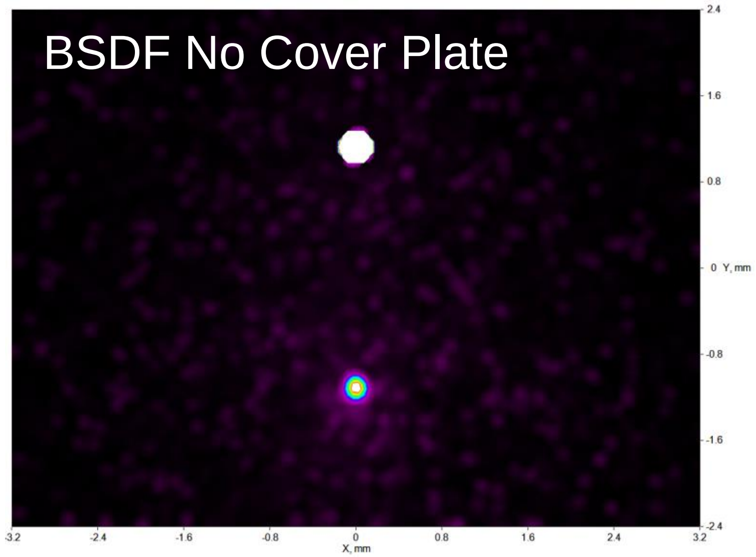
- All lens optical surfaces and the cover glass surfaces were defined to have a single layer AR coating (default) and are set to split the rays
  - Lens, IR Filter and Cover Glass edge surfaces were defined to have a 5^{o} Gaussian scattering surface with Fresnel reflectivity
- Mechanical surfaces (mount and spacers) were defined using the LightTools Complete Scatterer
  - 5% Reflectivity
  - Of the reflected light, 30% is diffuse (Lambertian)
  - 70% is Gaussian scattering with a standard deviation of 15^{o} (half-width)
  - This is an arbitrary surface finish for the purposes of demonstration, using a measured BSDF optical property would be preferred for a real system analysis
- The front surface of the detector were set to use the BSDF data generated using DiffractMOD
  - The BSDF file has ~36% reflectivity at normal incidence and 550nm
- A collimated source at 550nm was used to illuminate the system

CMOS Reflection Effect

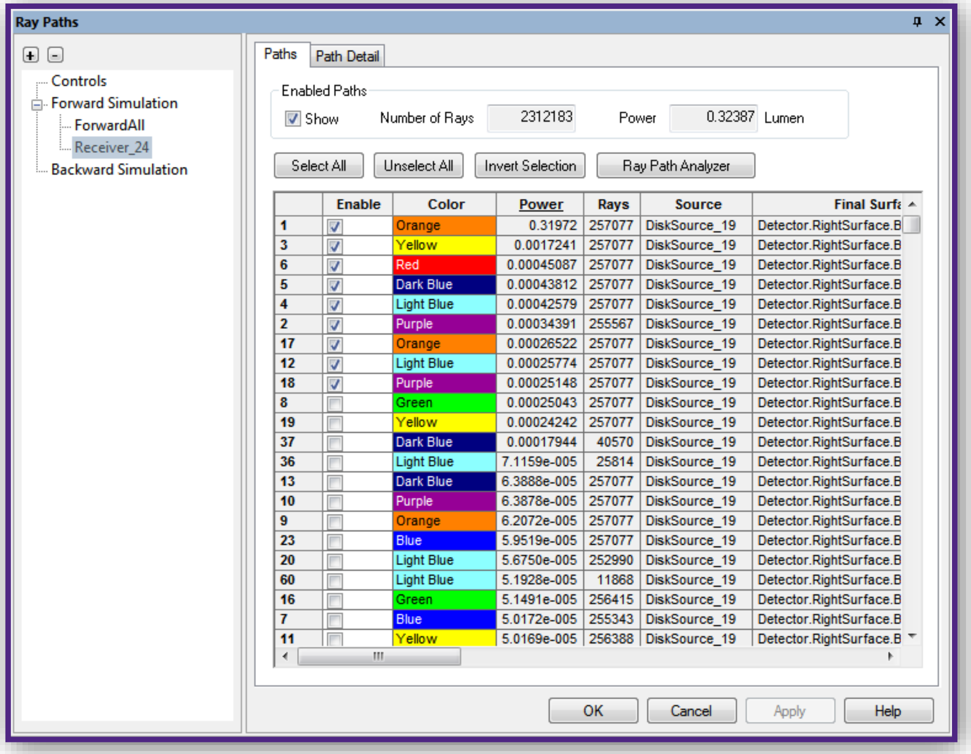
- The structure of the CMOS chip can have a significant impact on the stray light detected
  - This is especially true if care is not taken to properly coat the cover plate because of the cover plate's proximity to the detector
  - Here we see a comparison of a detector with a specular reflection, one with the BSDF result from RSoft, and one with the BSDF but no cover plate reflection
  - Reflectivity values are approximately the same in all three cases







Ray Path Analysis

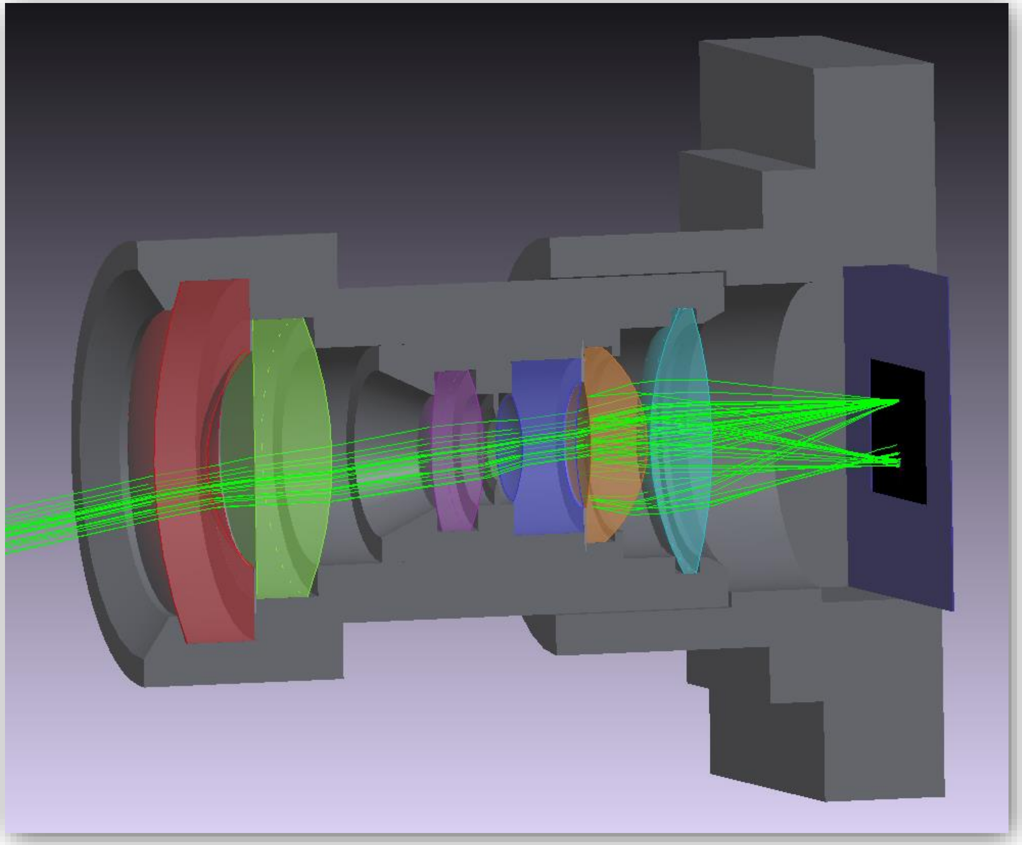


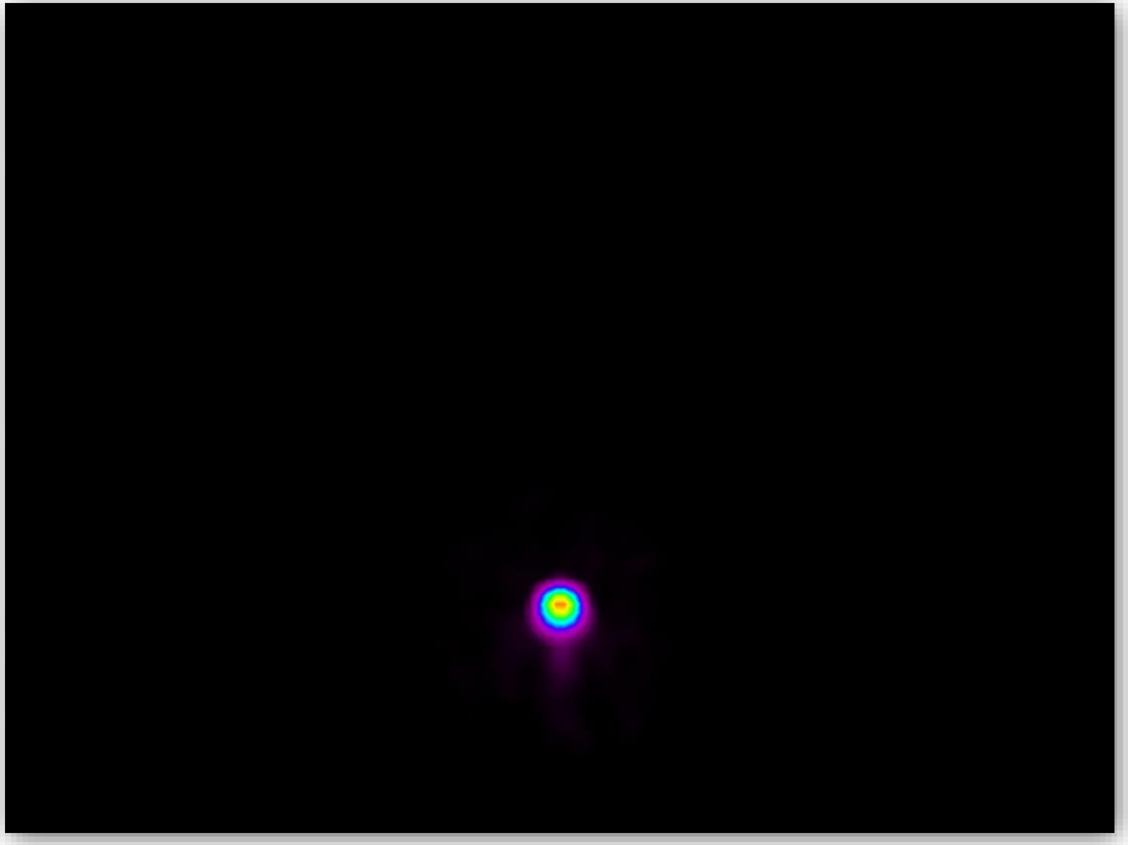
- Ray Path is the primary tool for analyzing stray light in LightTools
- Ray Path can record each ray's paths
  - Record paths start at source then pass through surfaces and zones
- Each path include
  - Sequential surfaces and zones
  - Number of ray
  - Power
- Ray Path filter can filter "path" on receiver
  - Filters the rays based on membership in an enabled path
- Rays can be sorted by power (either in ascending or descending order) so that the most energetic paths are listed at the top
  - Useful for quickly finding the most important paths since the catalog lists paths in the order that they were discovered

Ray Path Analysis *cont.*

Single ray path shown in 3D View View

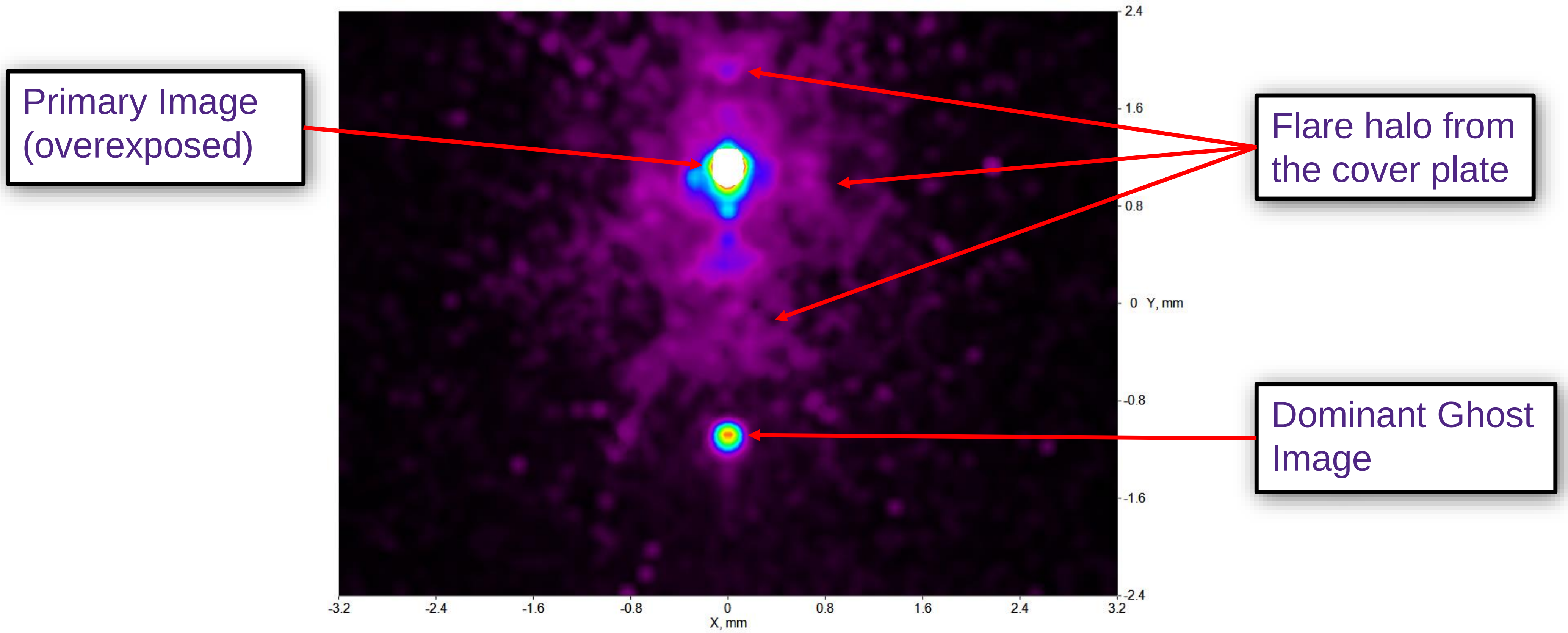
Image on detector with ray path filter applied





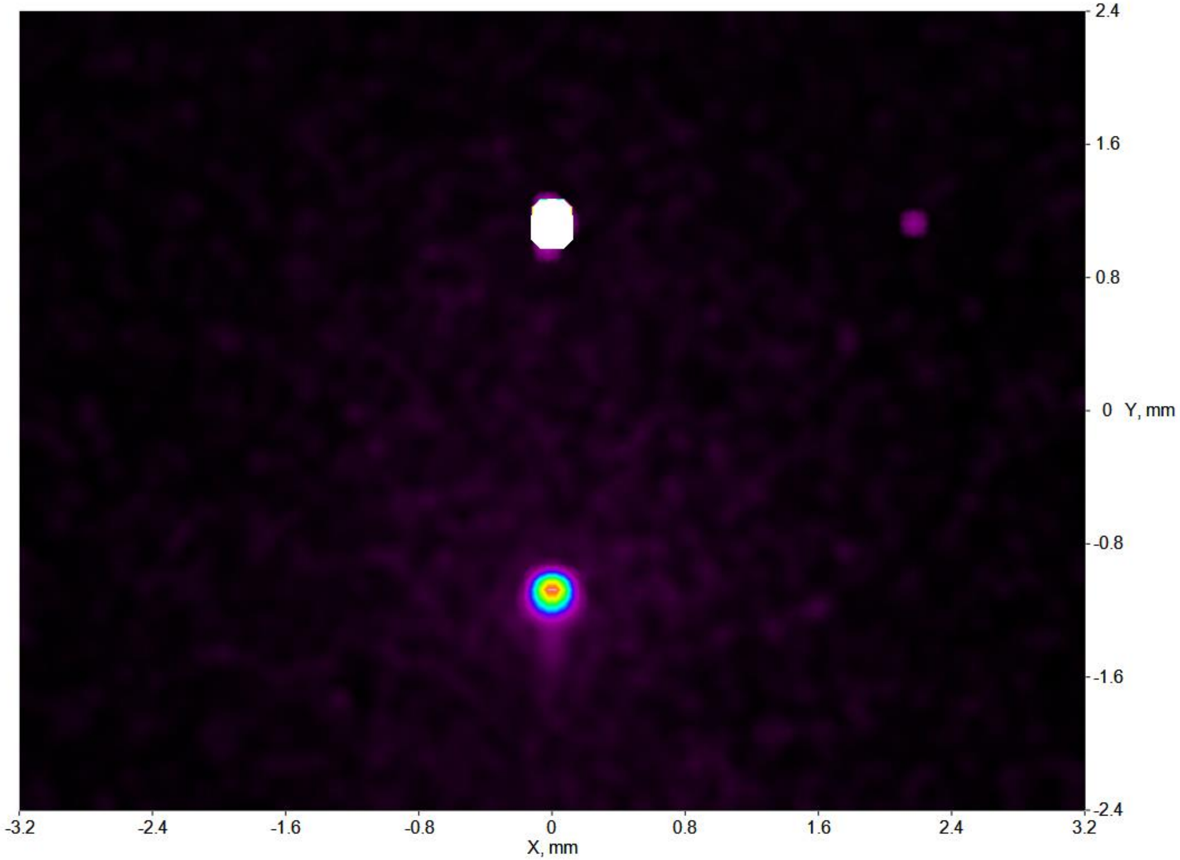
Stray Light at 10º

- Here we see the image produced with the source at 10º
- The image is shown on a linear scale with the main image over exposed



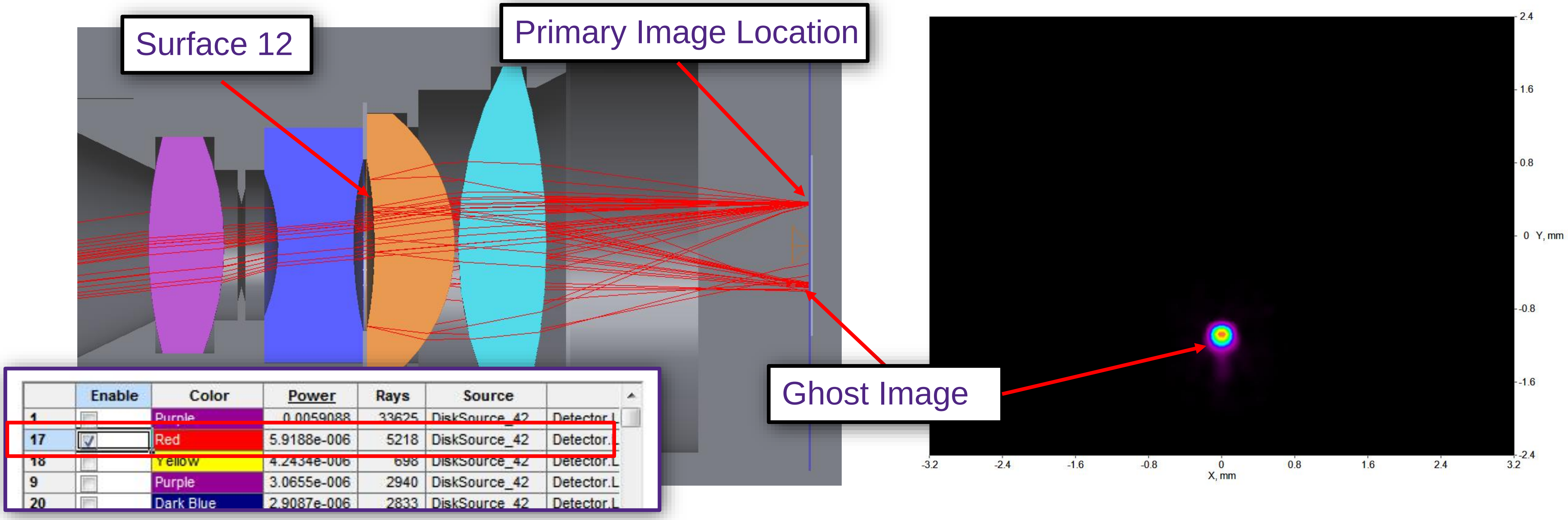
Effect of the Cover Plate

- Much of the large area stray light seen around the primary image is due to the wide-angle reflection from the detector reflecting back off of the two flat, coated surfaces of the cover plate which are in close proximity to the detector
- The single layer MgF2 coating on these flat surfaces gives a ~1.33% reflectivity at normal incidence
  - This, coupled with the 36% reflectivity of the detector is much too high
- By upgrading the coating on the cover plate to reflect 0.2% we can achieve a substantial reduction in the halo

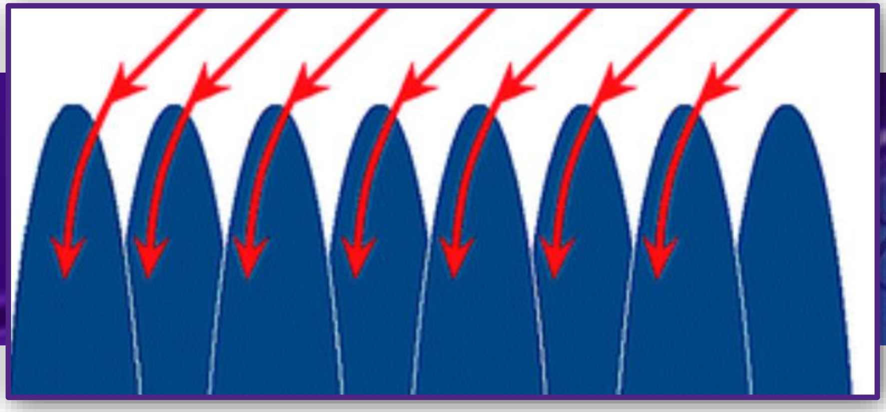


Identifying the Dominant Ghost Image

- The source of the single, dominant ghost image in the field can be identified using Ray Path and Ray Path Analyzer
- LightTools confirms the CODE V GHO result that the Detector-Surface 12 pair is the cause of the dominant ghost image



Outline



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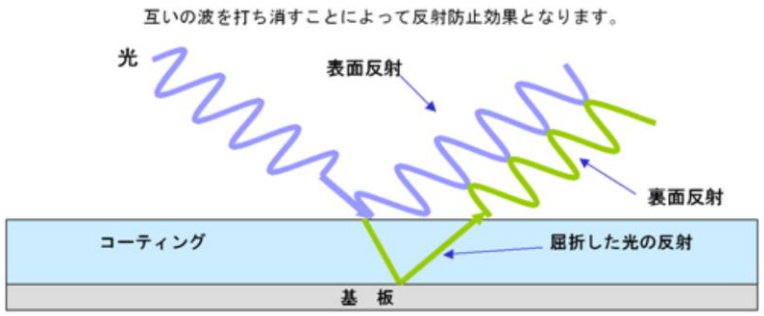
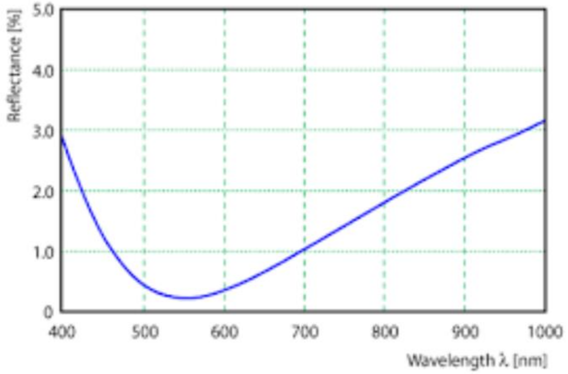
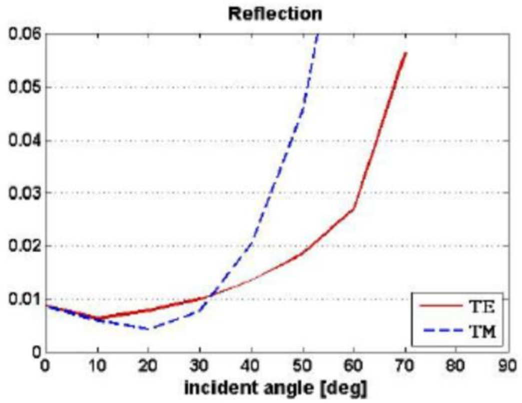
- Conclusion

Anti-Reflection Coatings

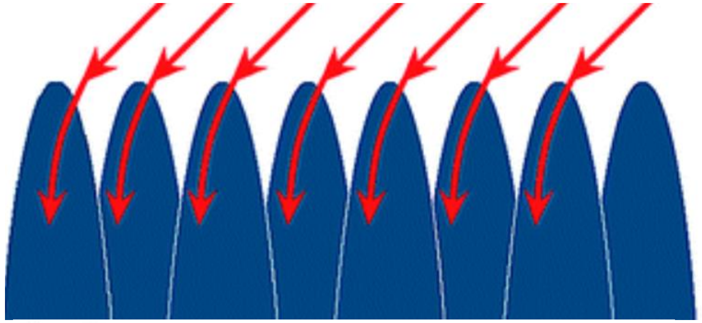
- Think Film
  - Simple, but dependent on wavelength, polarization, and incident angle

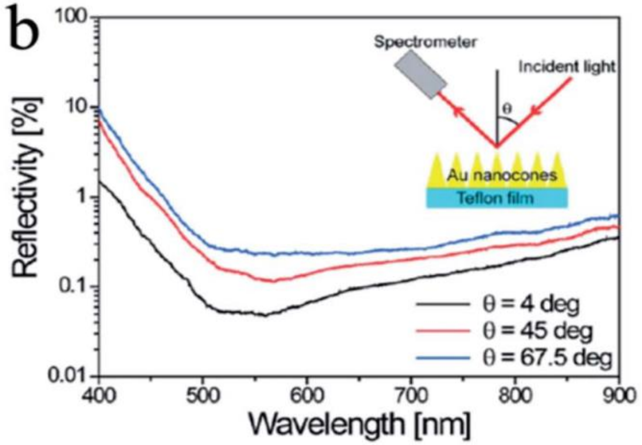






- Nano arrays
  - Complex, but broad band and insensitive to polarization and incident angle

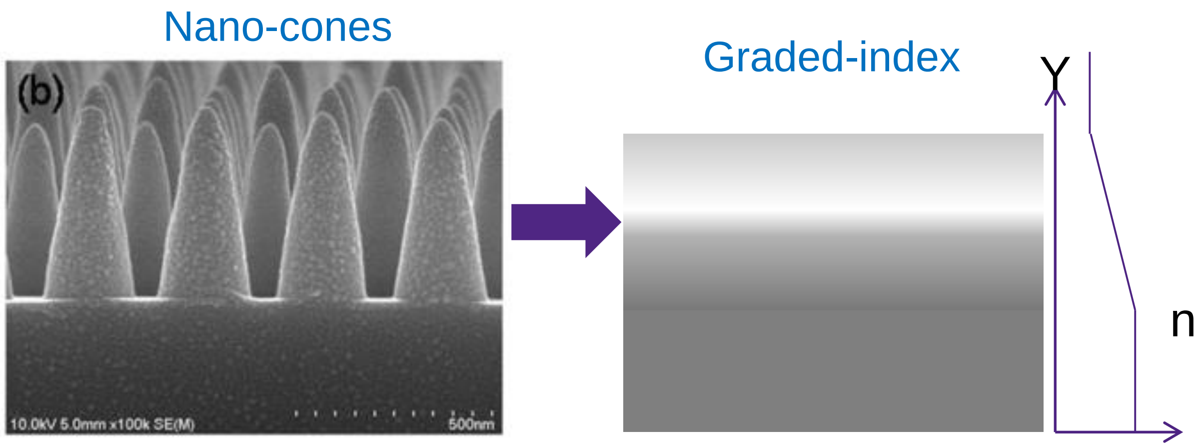




Cai, Jinguang, and Limin Qi. "Recent advances in antireflective surfaces based on nanostructure arrays." *Materials Horizons* 2.1 (2015): 37-53.

Subwavelength structure

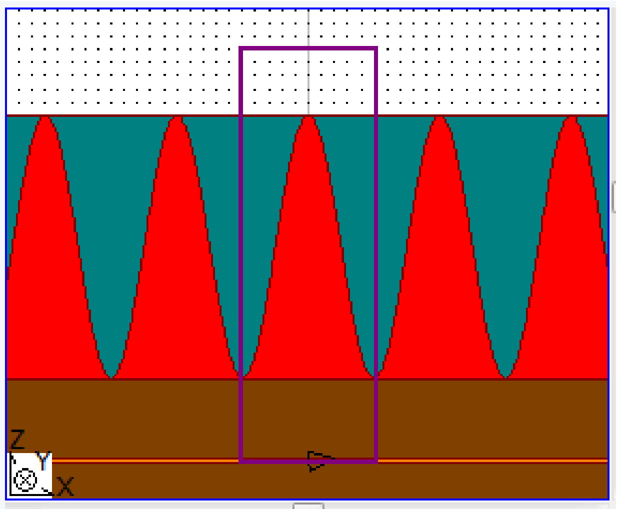
- Subwavelength nano-structure can be used to reduce the reflectivity of a surface
  - In a similar manner, such structures are used to maximize the extraction of LEDs
- Subwavelength periodic nano-cones or pyramids behaves like a medium with graded index
- Theoretically, there will be no reflection off a medium with graded index at any wavelength and at any incident angle



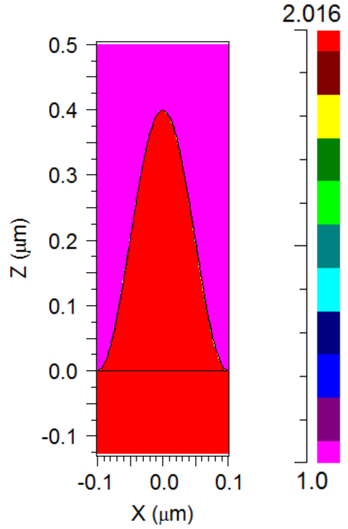
[1]Ou, Qing-Dong, et al., *Advanced Optical Materials* 3.1 (2015): 87-94.

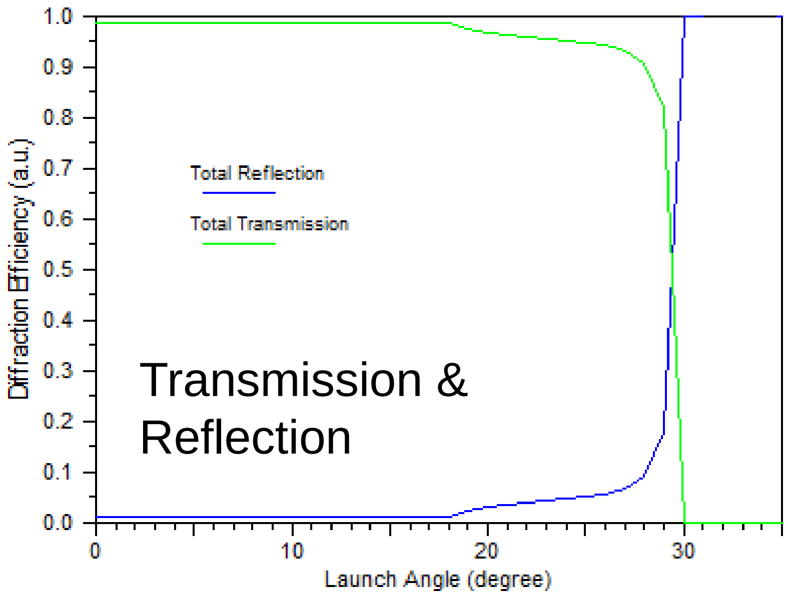
Improvement of Angular Transmission and Angular Uniformity

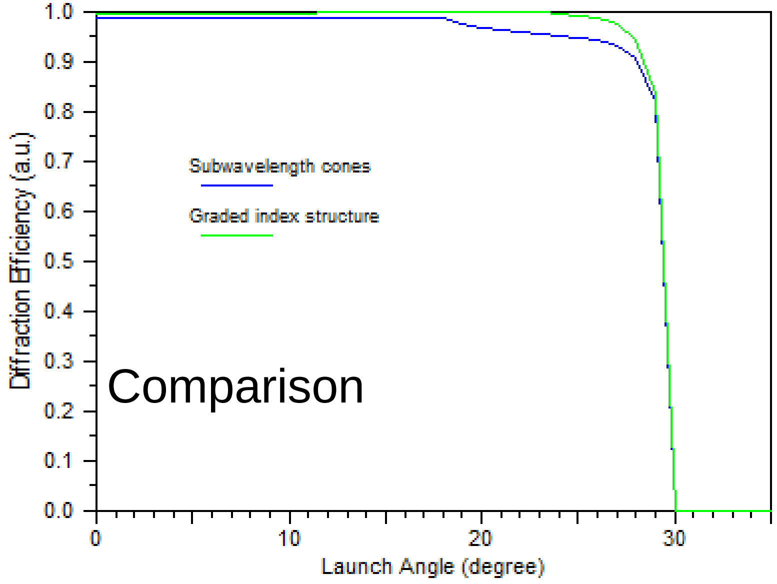
Sub-wavelength cones



Index profile







- Sub-wavelength cone indeed behaves like a graded index structure
- It could potentially improve the OLED performance

Diffraction of Periodic Arrays

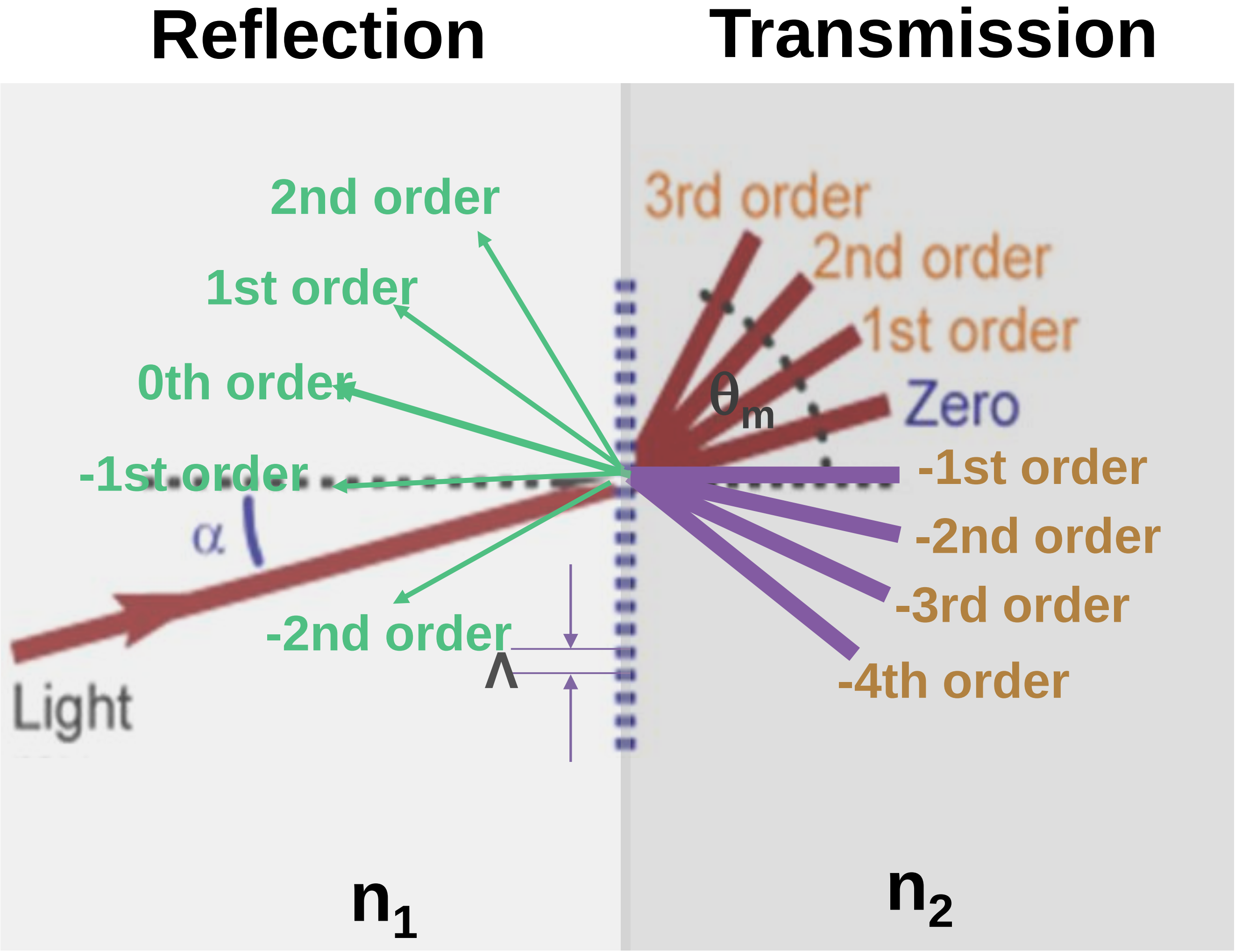
- Periodic gratings diffract light into different orders, in addition to refraction (0-th order)

$$\Lambda(\sin\alpha + \sin\theta_m) = m\frac{\lambda}{n}$$

  - Where α is the incident angle
  - m is diffraction order
  - θ_m is diffraction angle
  - n is the refractive index of the medium
- For normal incident (α=0), 1^{st} order:

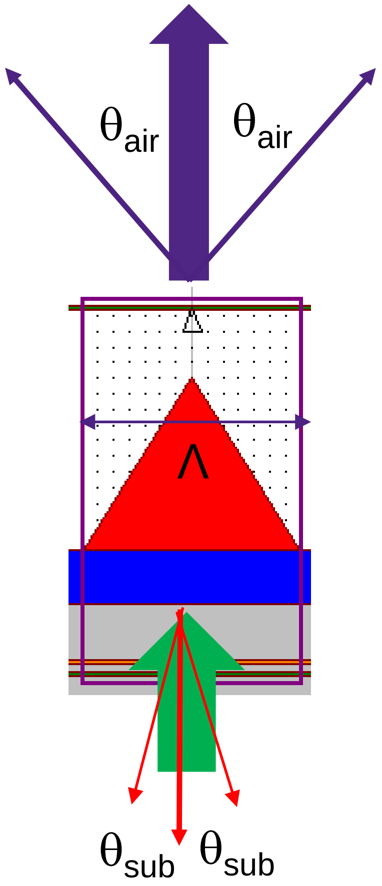
$$\theta_1 = \sin^{-1}\left(\frac{\lambda}{n\Lambda}\right)$$

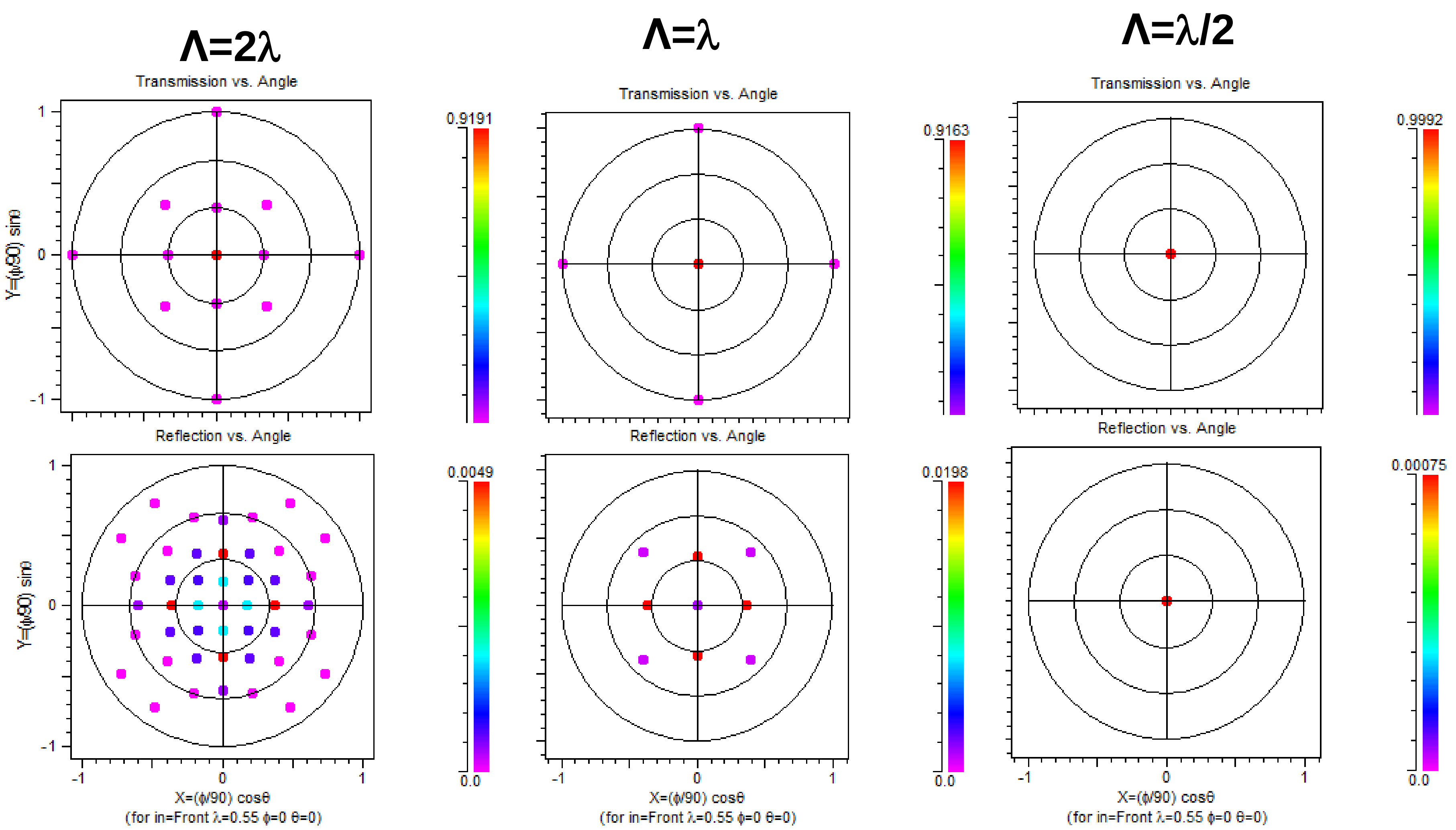
  - subwavelength grating $\left(\Lambda < \frac{\lambda}{n}\right)$ has no diffraction!



Behavior of Nano-Structure

Front incident

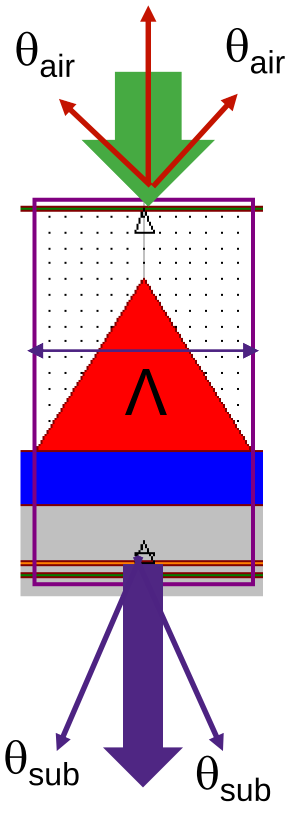




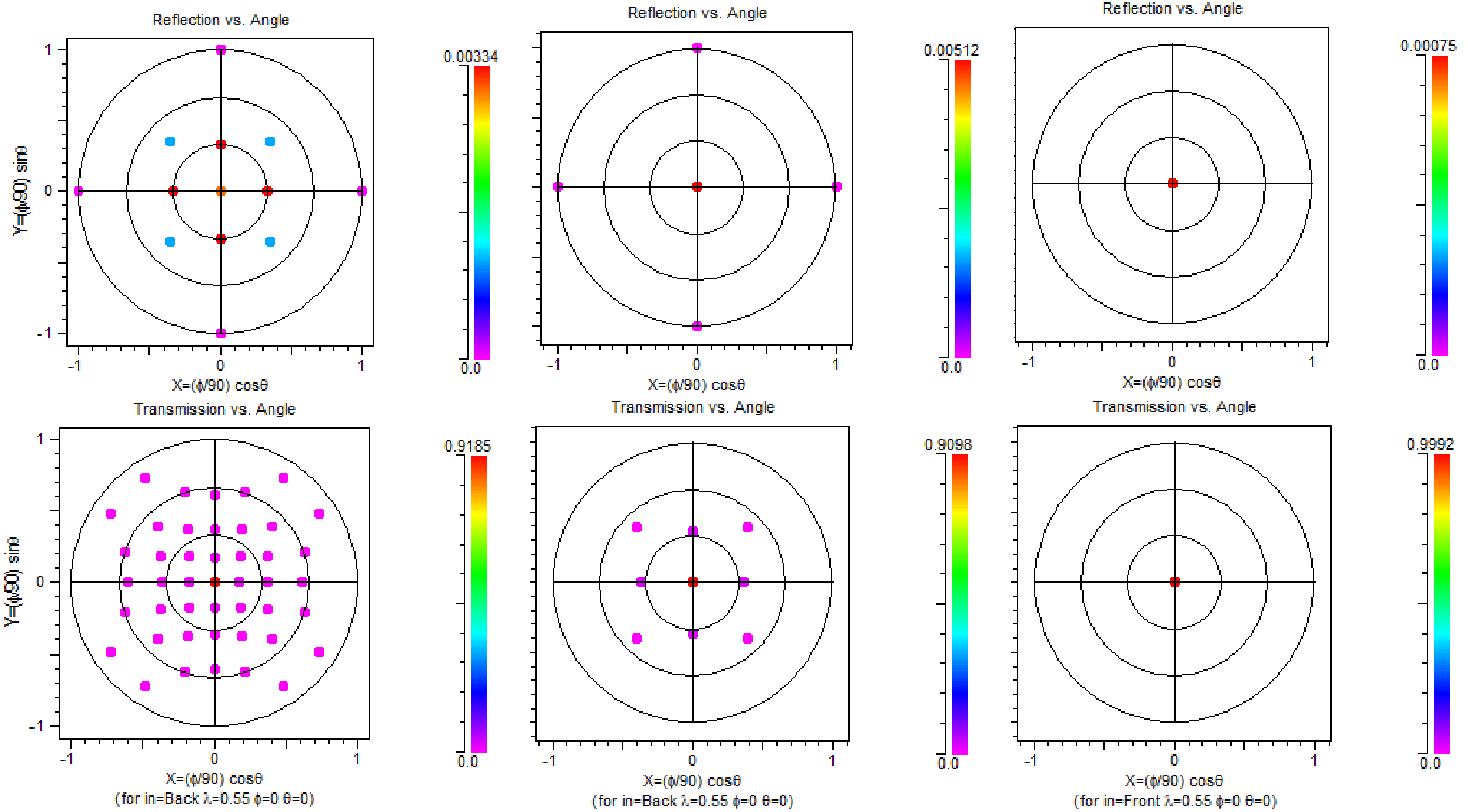
(1) Lower index medium diffracts light more; (2) Subwavelength grating does NOT diffract light.

Behavior of Nano-Structure

Back incident



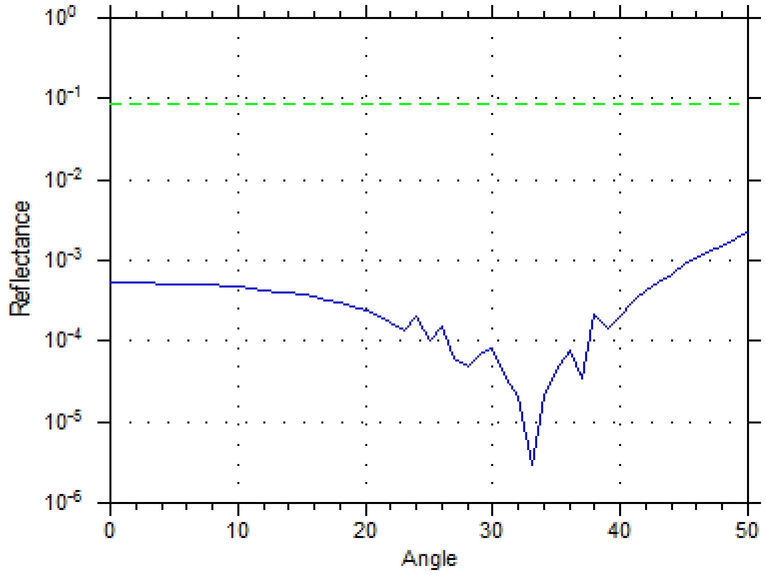
Λ=2λ Λ=λ Λ=λ/2



Same behavior is observed

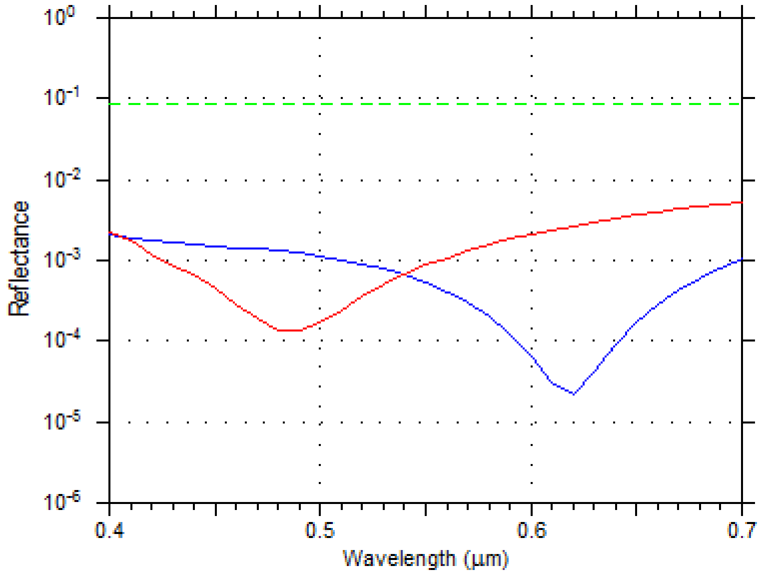
Performance of Sub-Wavelength AR Coating

- Angular sensitivity



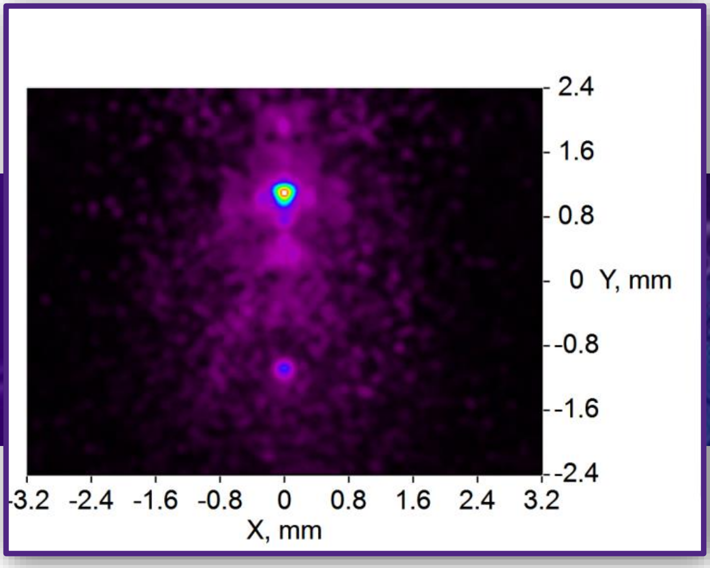
- Works well over a very wide angular range

- Wavelength sensitivity



- Works well over a wide wavelength range

Outline



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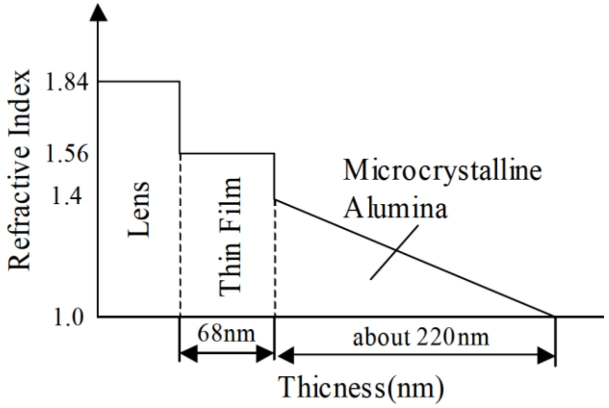
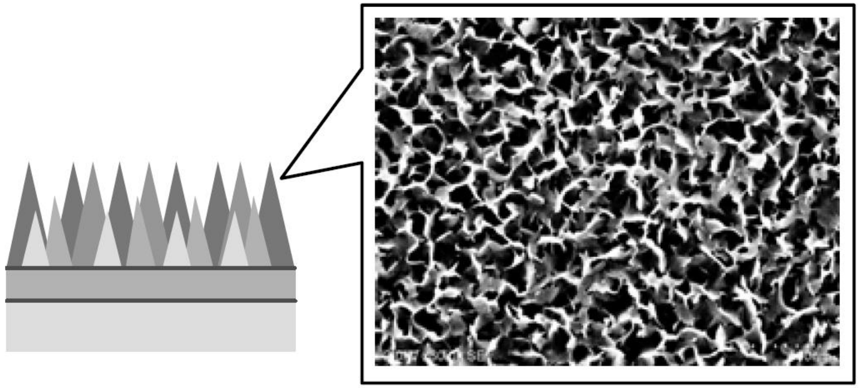
Case Study: Structure Used by Canon

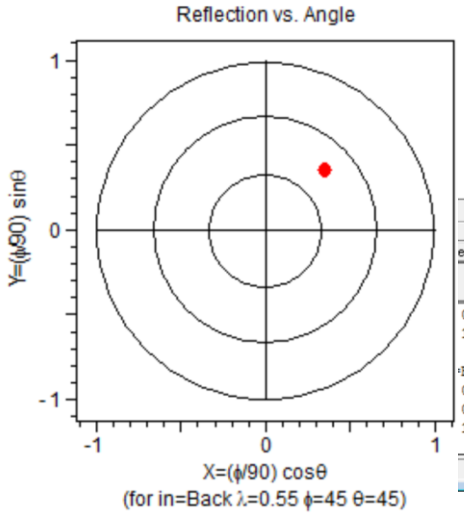
Canon EF24mm F1.4L II USM lens

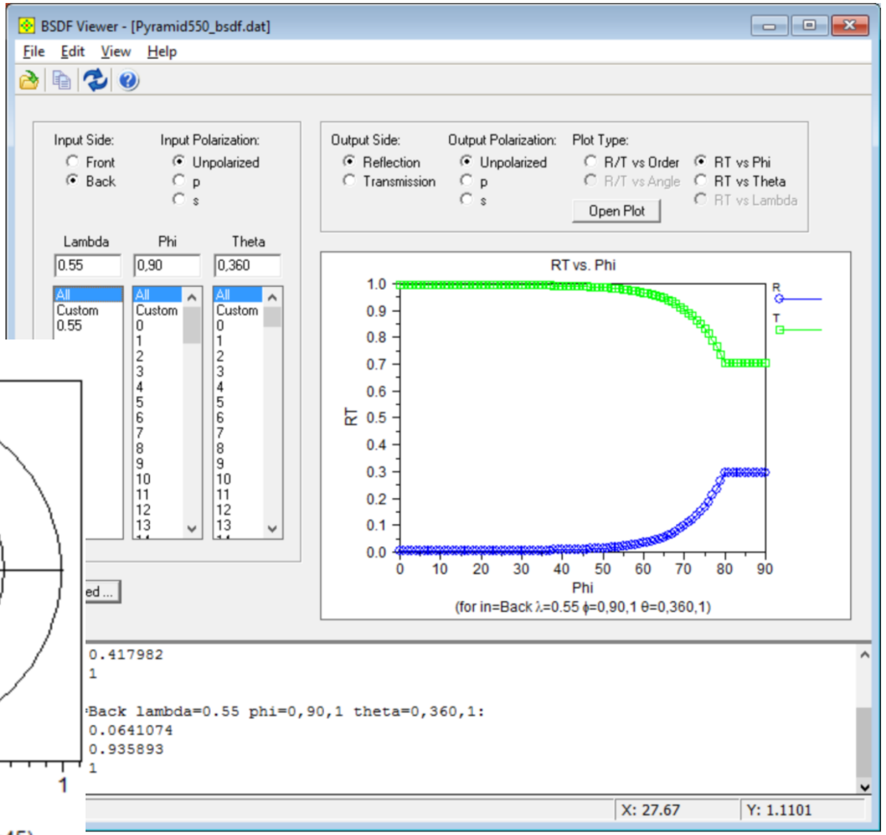




Okuno, Takeharu. "Development of subwavelength structure coating (SWC) and its application to imaging lenses." *International Optical Design Conference*. Optical Society of America, 2010.

BSDF





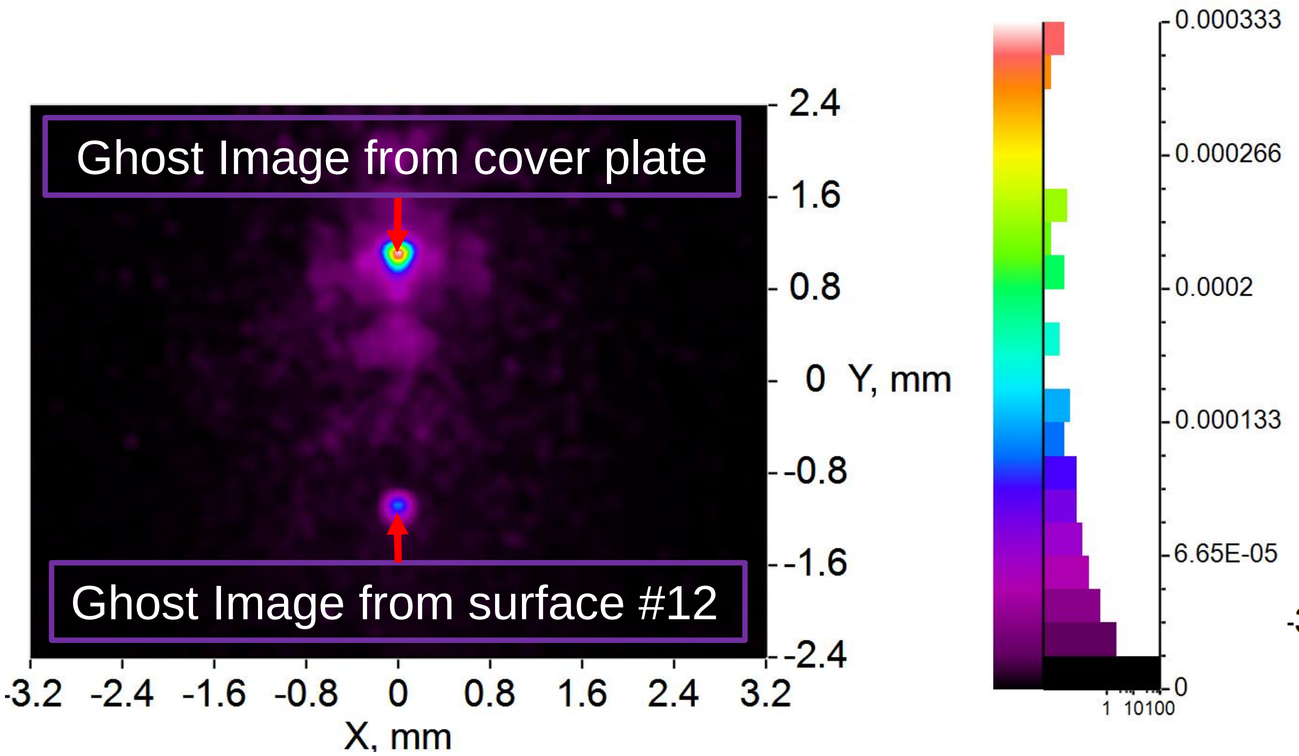
BSDF calculation confirmed:

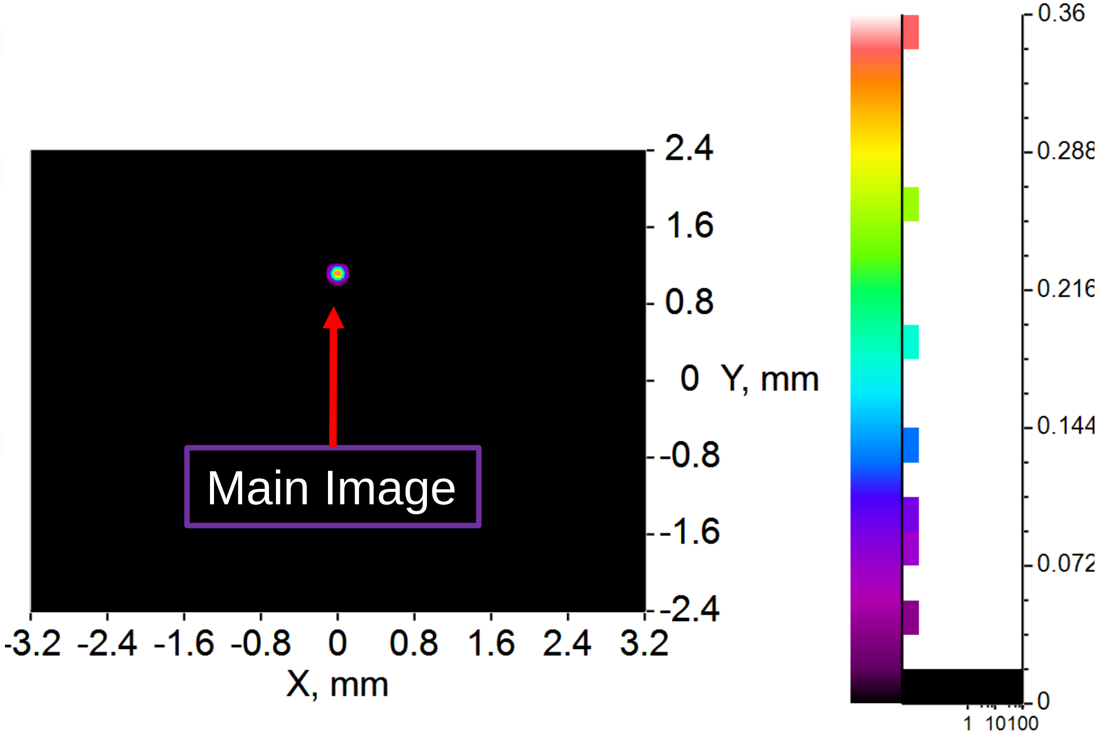
- Little reflection over large angular range
- No high-order diffraction

Ghost Image Reduction

Without textured surfaces

- With standard quarter-wavelength AR-coating on lens surface #12, the ghost image from it is at the level of 1.2×10^{-4}, ~3000 time weaker than the main image
- The ghost image from the cover plate is 3.3×10^{-4}, ~1000 time weaker than the main image

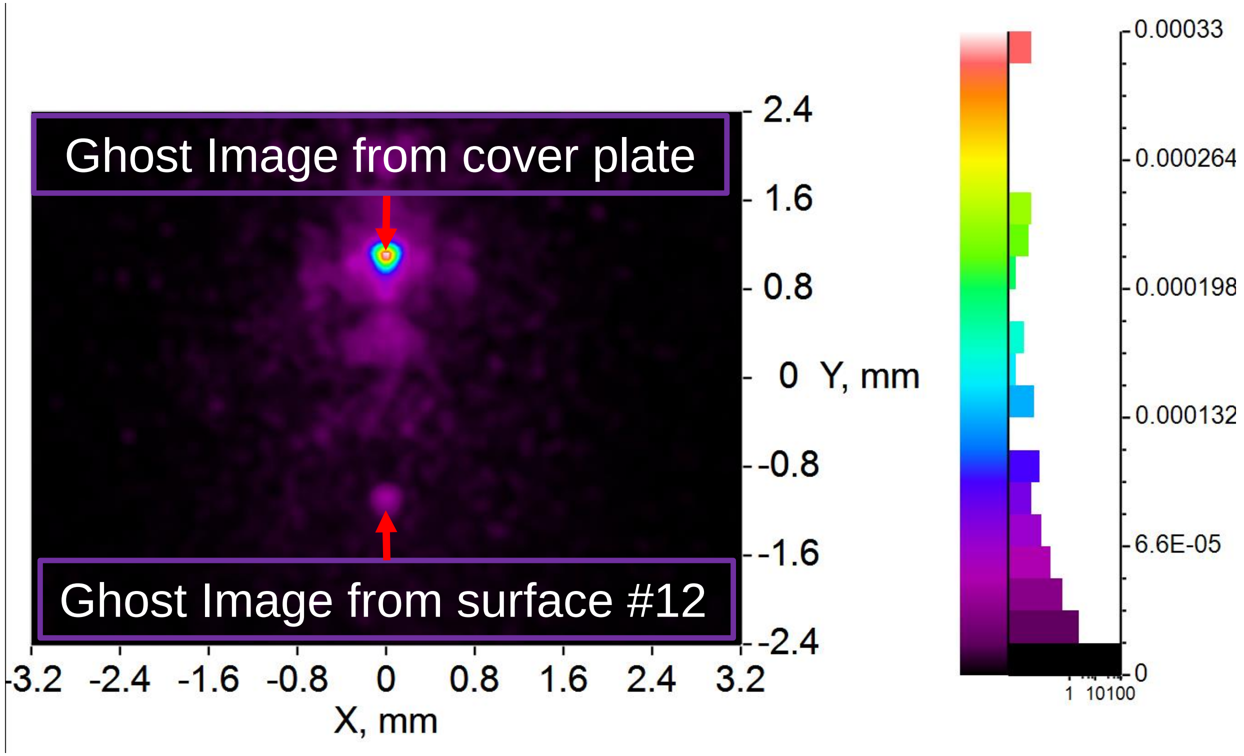




Ghost Image Reduction

With lens surfaces textured

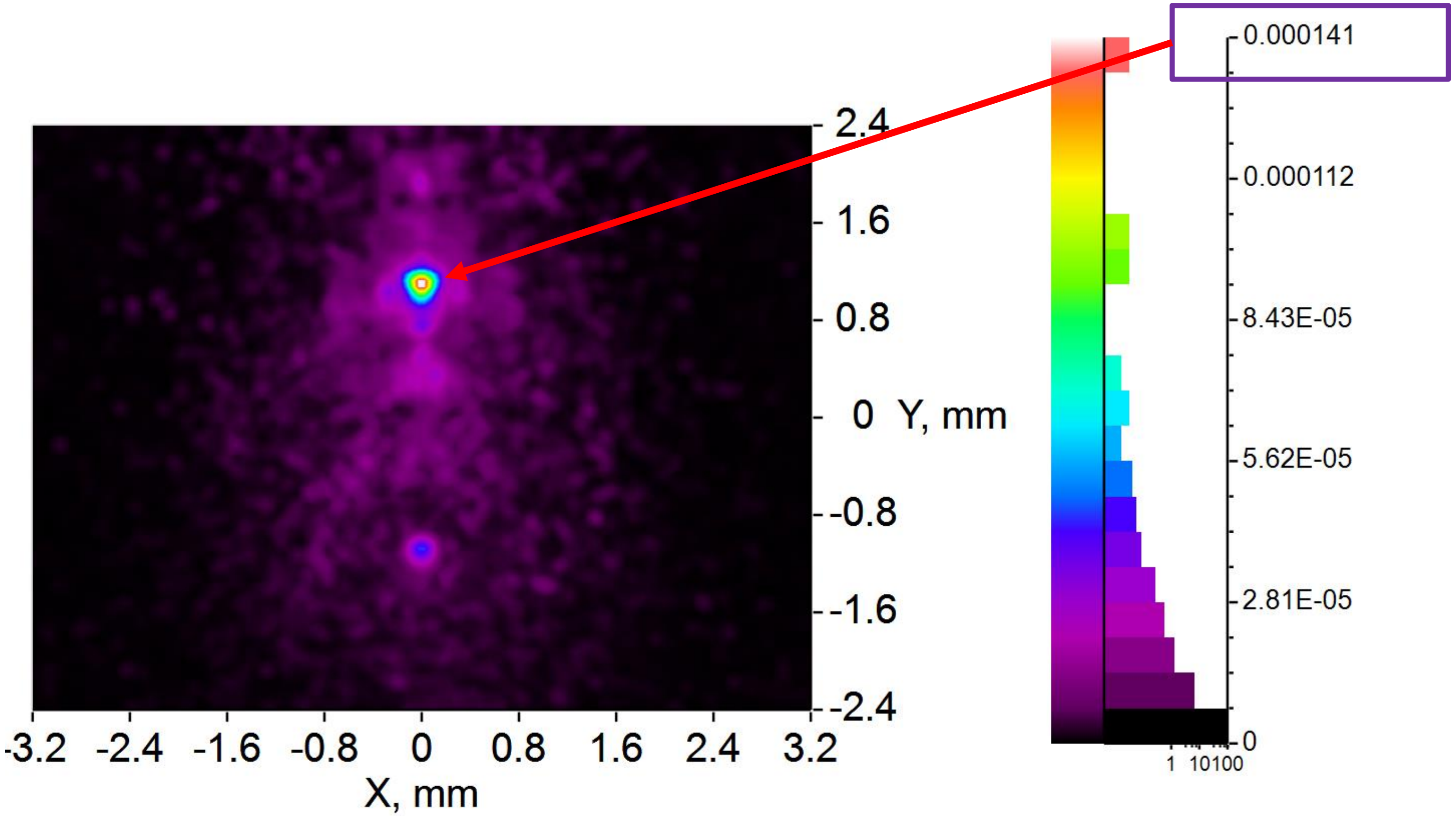
- With lens surface #12 textured, the ghost image from it is suppressed to the level of 4.3×10^{-5}, about 3x weaker than before, ~8000 weaker than the main image
- There is no effect on the ghost image from the cover plate, still 3.3×10^{-4}, ~1000 time weaker than the main image



Ghost Image Reduction

With lens surface and cover plate textured

- With both lens surface #12 and cover plate textured, the ghost image from the cover plate is suppressed to the level of $1.4x10^{-4}$, more than 2x weaker.



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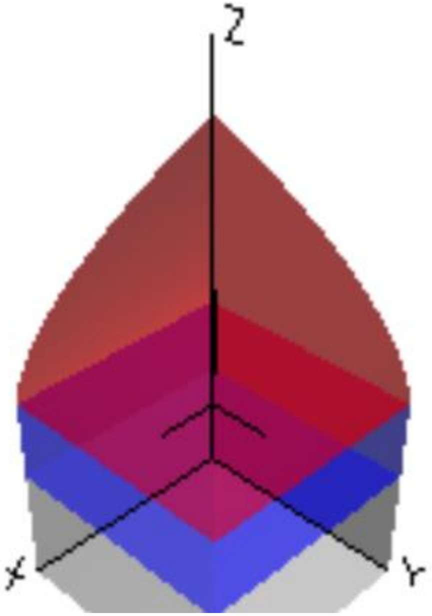
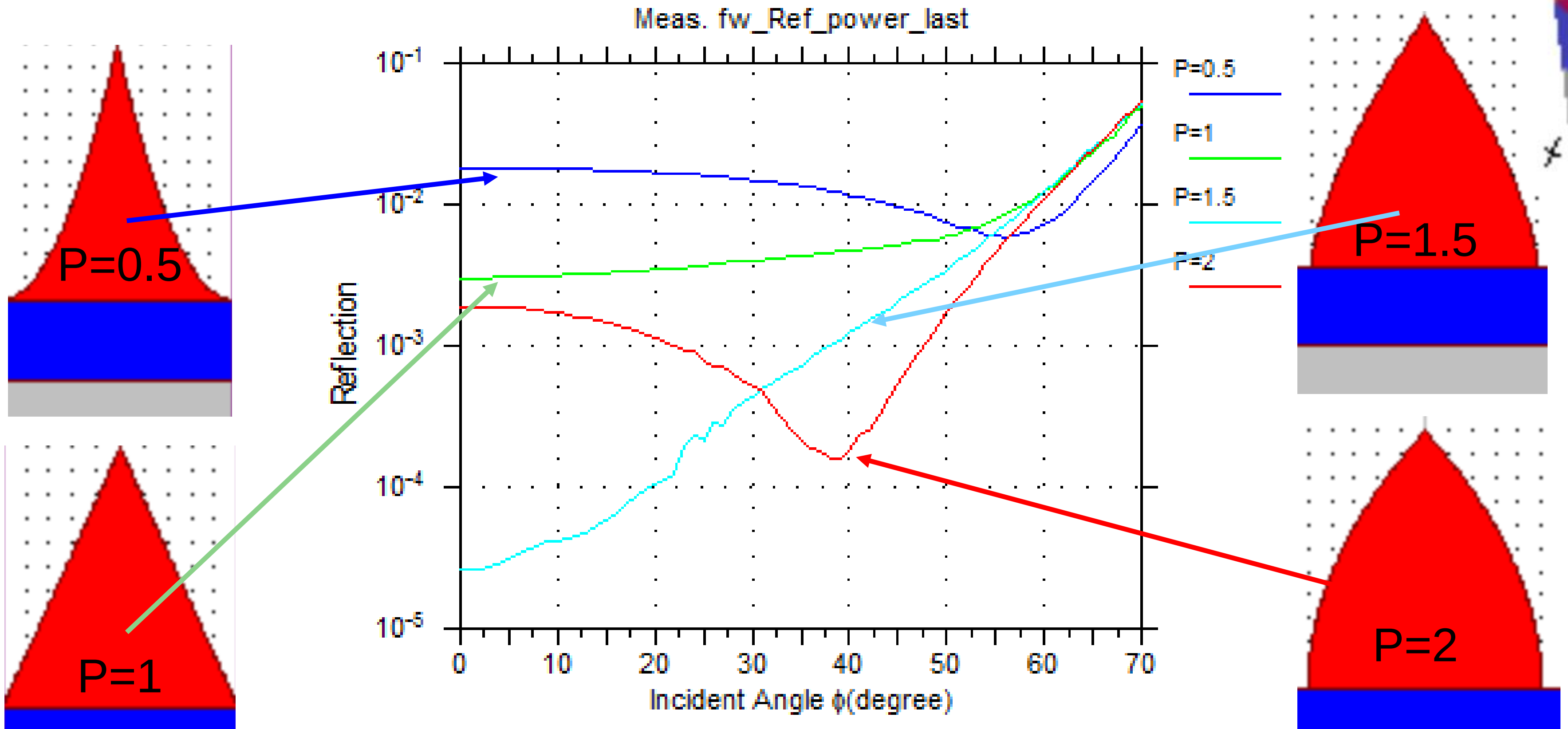
Optimization of the Nano-Structure

Pyramid reshaping

- Power function $f(z)=z^p$ for the pyramid taper

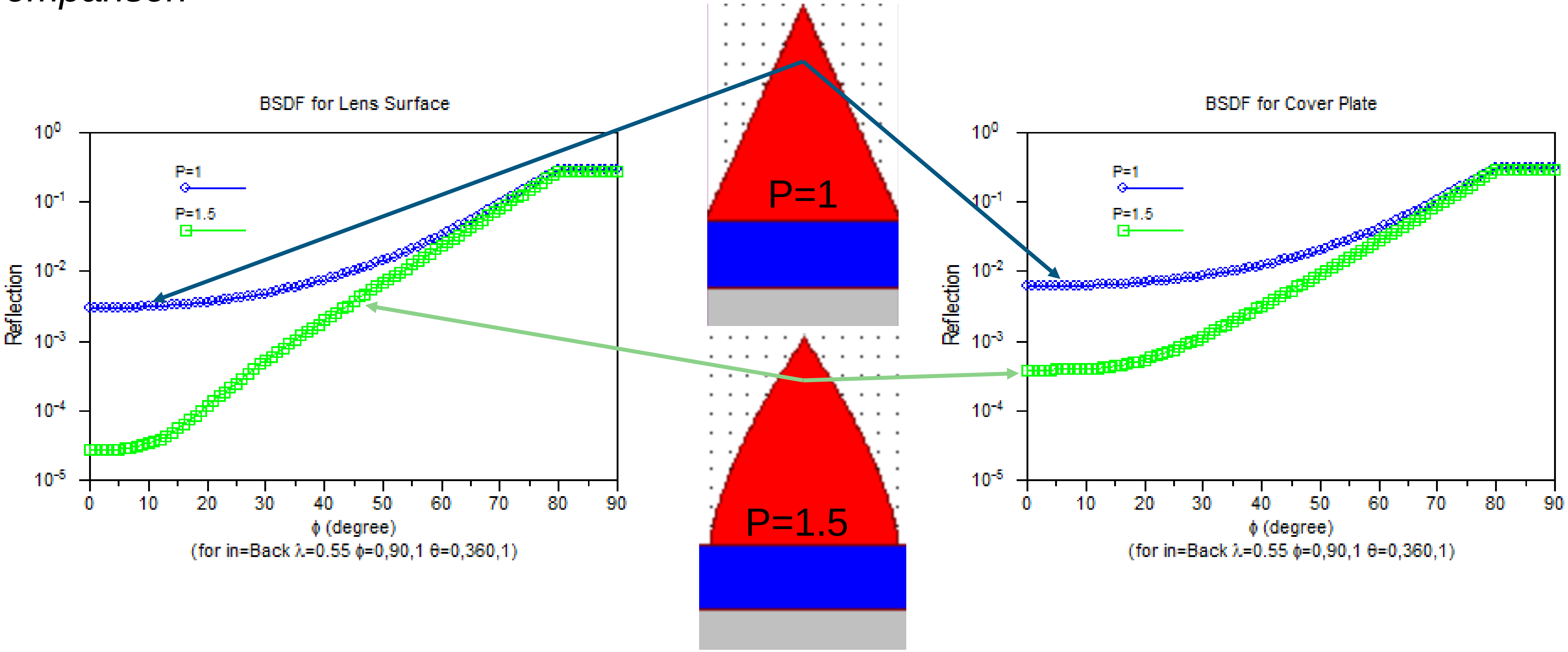




Taper function $f(z)=z^{1.5}$ gives lowest reflection, ~100x smaller than linear for normal incident!

BSDF of the Optimized Pyramid

Comparison

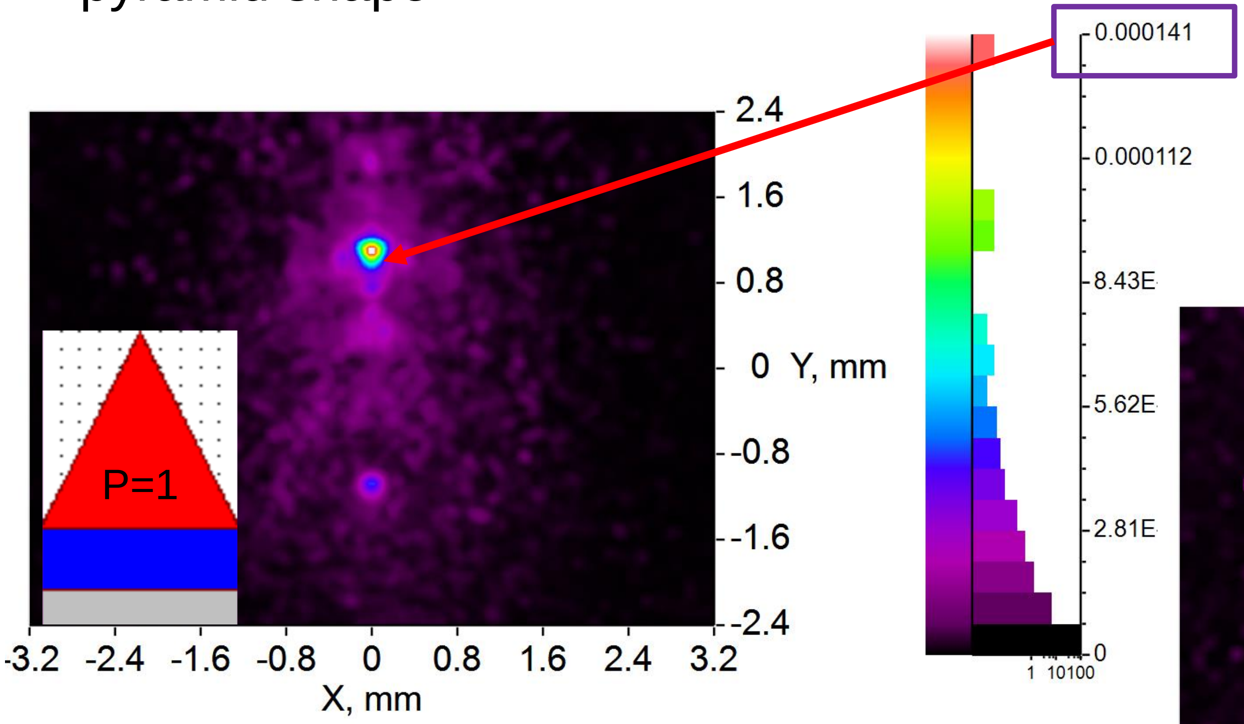


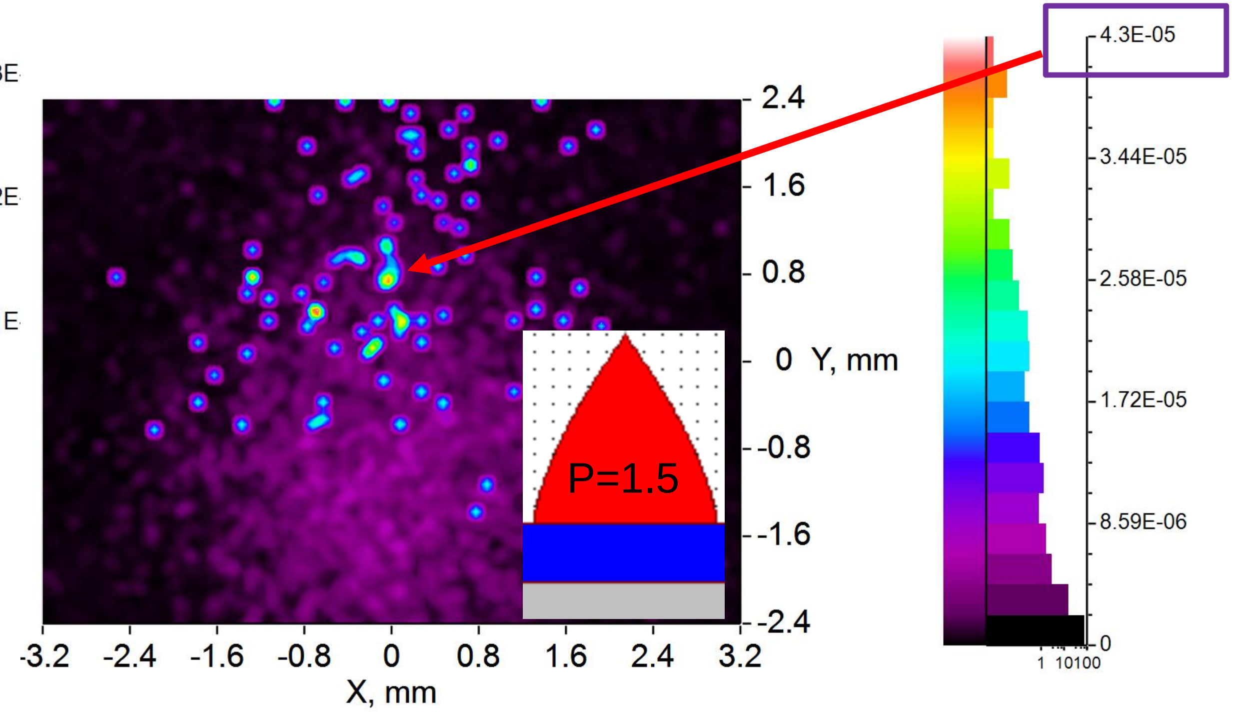
- Compared with the linear taper (P=1), the optimized pyramid with P=1.5 performs much better on both lens surface and cover plate

Ghost Image Reduction

Lens surface and cover plate textured with optimized structure

- With the optimized pyramid shape, the ghost images are 3x weaker than with the linear pyramid shape



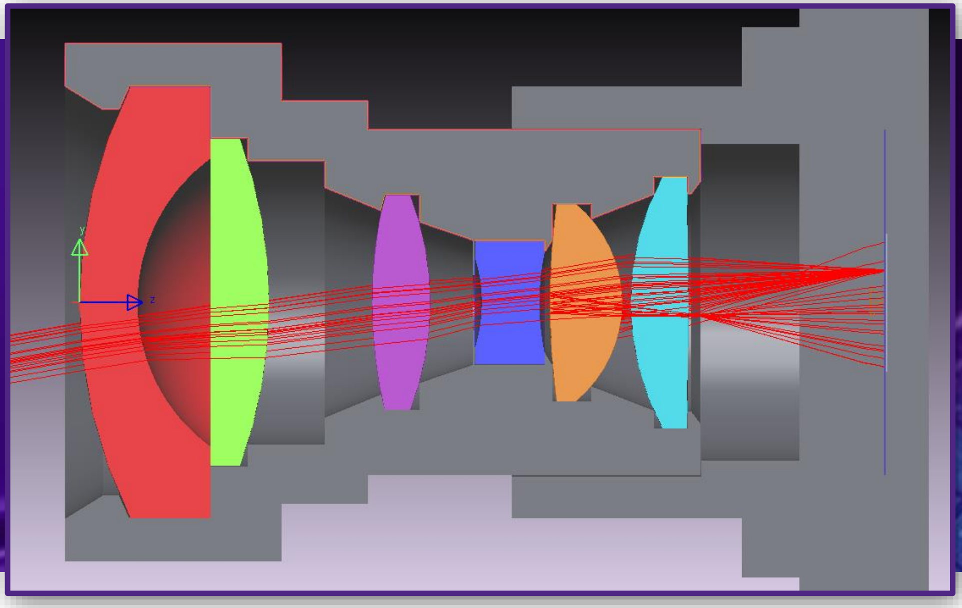


Conclusion

- The analysis of stray light in imaging systems is a complex but important task
- By using CODE V, RSoft device tools and LightTools we can effectively simulate different aspects of the problem:
  - Imaging lens system designed using CODE V can be exported into LightTools for stray light analysis
  - RSoft can be used for modeling reflection from the detector structure and creating a BSDF file for use in LightTools
  - Ghost image can be visualized and the its source can be identified in LightTools
- The subwavelength structure can be modeled and optimized using RSoft tools in order to minimize the reflection and reduce the ghost image

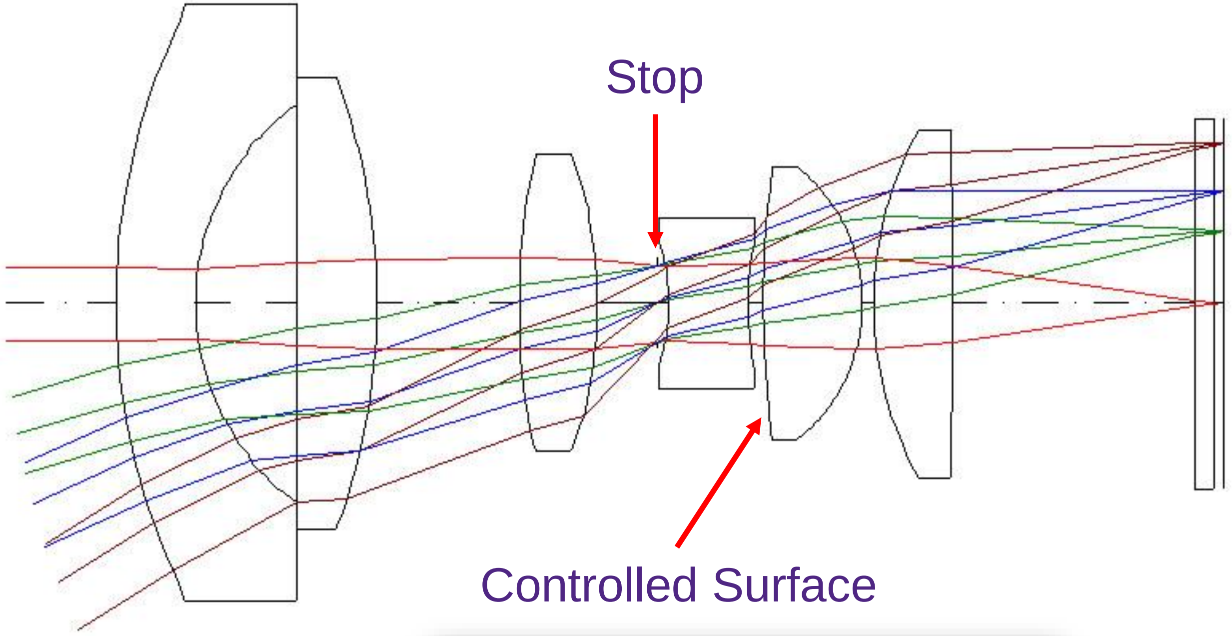
Appendix

Using CODE V @GHOST Function to Reduce the Ghost Image



Reducing the Dominant Ghost Image with @GHOST

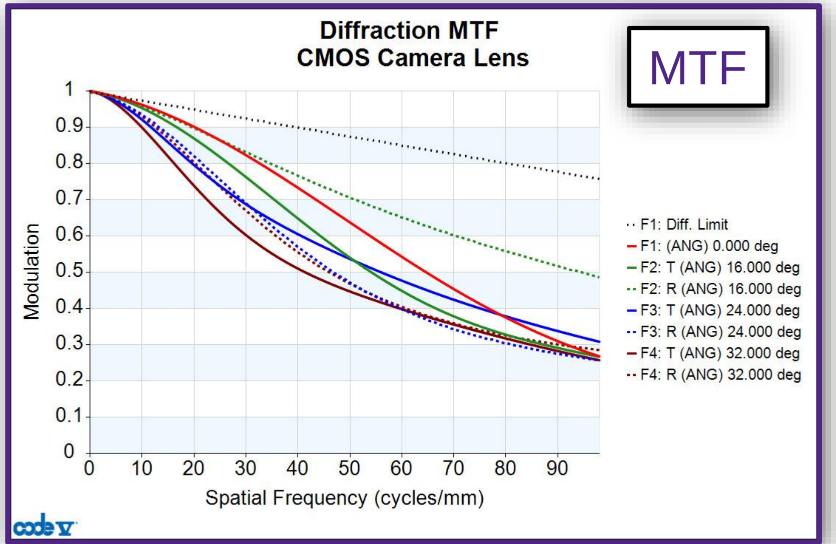
- Returning to CODE V we can re-optimize the lens while using the @GHOST function to control the disc size of the dominant ghost image
  - Number of Elements: 6
  - Focal Length: 6.4mm
  - Aperture: F/3.5
  - FOV: 32^{o} half-field at the corners
  - OAL: 28mm
  - Max Distortion: 0.59% (full field)
  - Relative Illumination: 84.5% (full field)
  - MTF: >25% @ 100 cycles/mm
  - Design Wavelengths: 656nm, 589nm, 434nm
  - Detector Size: 6.4mm x 4.8mm (1/2" Active Pixel Sensor CMOS)
  - Detector Pixels: 1280 x 960 (5μm x 5μm)



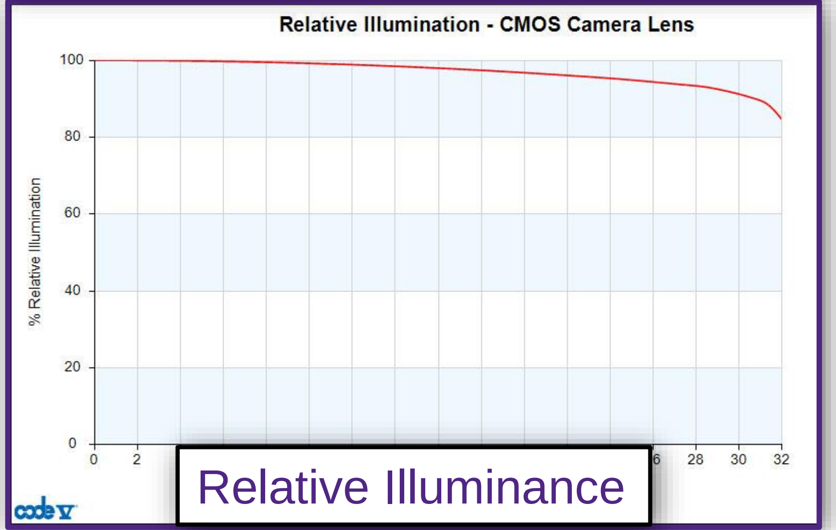
Elements 1 – 6: Lenses
Element 7: Cover Plate
Element 8: CMOS Detector

Critical Performance Measures

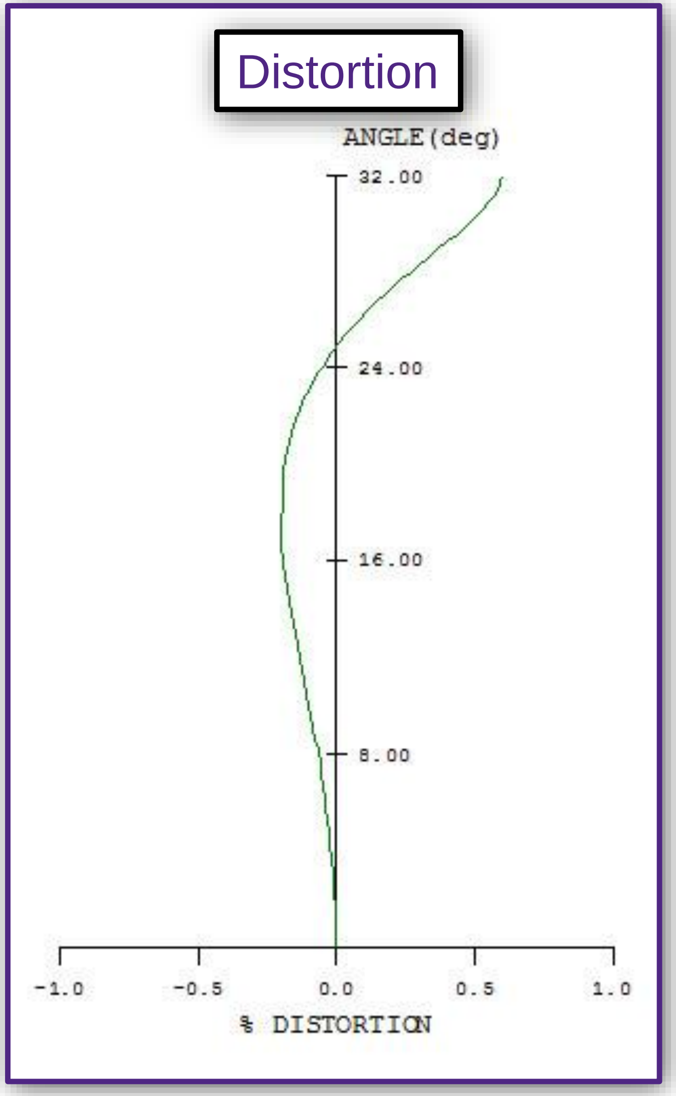
MTF



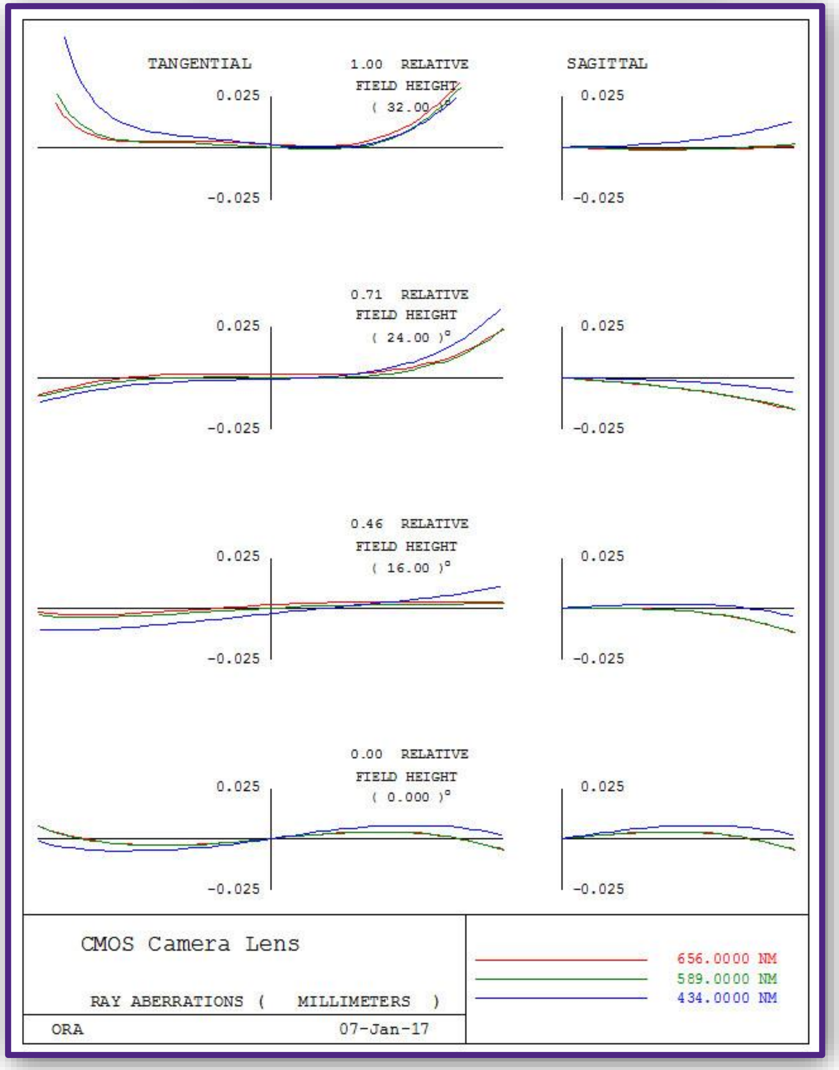
Relative Illuminance



Distortion



Ray Aberration Curves



Reducing the Dominant Ghost Image with @GHOST

- Returning the system to LightTools and adjusting the mount to fit the new lens, we can see that the ghost image peak has been greatly reduced