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

- 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 onto 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

Ghost Image Reduction by Nanostructures
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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° 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)
Critical Performance Measures

MTF

Relative Illuminance

Distortion

Ray Aberration Curves

Ghost Image Reduction by Nanostructures
Ghost Image Analysis

- The GHO option 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.

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<th>REFL 2</th>
<th>DBFL</th>
<th>EFL</th>
<th>DISC</th>
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@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
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
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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.

- **FullWAVE**
- **DiffractMOD**

Physical optics

Geometrical optics

Feature Size vs. Wavelength

Smaller...

Larger (> ~10 \( \lambda \))

Ghost Image Reduction by 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

- 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
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.
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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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° 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° (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

Image on detector with ray path filter applied

Ghost Image Reduction by Nanostructures
Stray Light at 10°

- Here we see the image produced with the source at 10°
- 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.

Ghost Image Reduction by Nanostructures
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.

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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

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

Improvement of Angular Transmission and Angular Uniformity

- 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 \( \alpha \) is the incident angle
  - \( m \) is diffraction order
  - \( \theta_m \) is diffraction angle
  - \( n \) is the refractive index of the medium
- For normal incident (\( \alpha=0 \)), 1\textsuperscript{st} order:
  \[ \theta_1 = \sin^{-1} \left( \frac{\lambda}{n\Lambda} \right) \]
  - subwavelength grating (\( \Lambda < \frac{\lambda}{n} \)) has no diffraction!
Behavior of Nano-Structure

*Front incident*

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

(1) Ghost Image Reduction by Nanostructures
Behavior of Nano-Structure

Back incident

\[ \Lambda = 2\lambda \]

\[ \Lambda = \lambda \]

\[ \Lambda = \lambda/2 \]

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
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Case Study: Structure Used by Canon

Canon EF24mm F1.4L II USM lens


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 $1.2 \times 10^{-4}$, ~3000 time weaker than the main image.
- The ghost image from the cover plate is $3.3 \times 10^{-4}$, ~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 $4.3 \times 10^{-5}$, about 3x weaker than before, ~8000 weaker than the main image.
- There is no effect on the ghost image from the cover plate, still $3.3 \times 10^{-4}$, ~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 $1.4 \times 10^{-4}$, 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!
• 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° 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)
Critical Performance Measures

MTF

Distortion

Ray Aberration Curves

Relative Illuminance

Ghost Image Reduction by Nanostructures
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.