Getting Started with AR/MR Lightguide Design

Hands-on, step-by-step tutorial

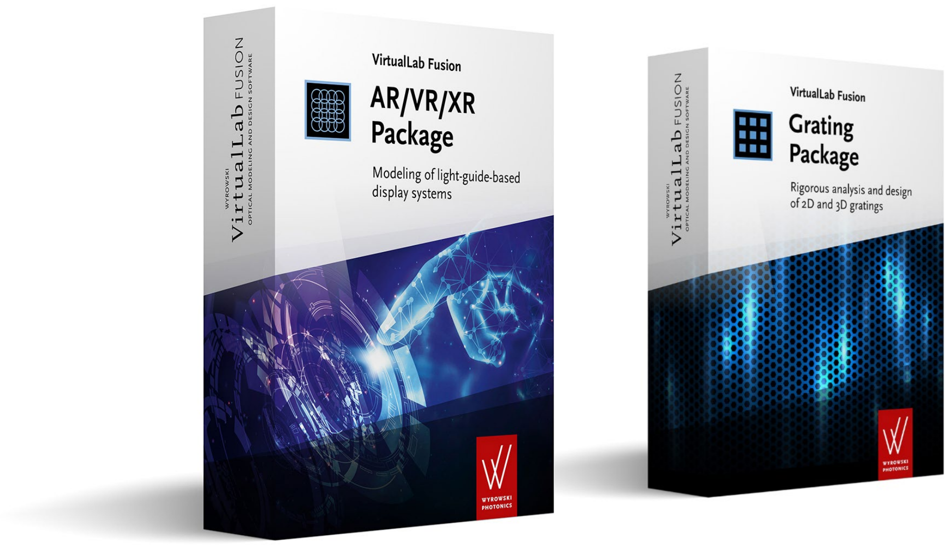
Getting Started with AR/MR Lightguide Design

Goals

This tutorial provides an introduction to lightguide design for augmented or mixed reality (AR/MR). Its main goal is to help you understand how these lightguides are structured and how they can be simulated using VirtualLab Fusion.

To keep things accessible, the designs and workflows demonstrated here are intentionally simplified.

By the end of this tutorial, you should have a solid foundation that enables you to explore more advanced and realistic lightguide design use cases.



Requirements

- VirtualLab Fusion license plus the AR/VR/XR and the Grating Packages (or a valid evaluation license)
- Basic familiarity with VirtualLab Fusion (e.g., completion of *Educational Tutorial #1 & #2*)

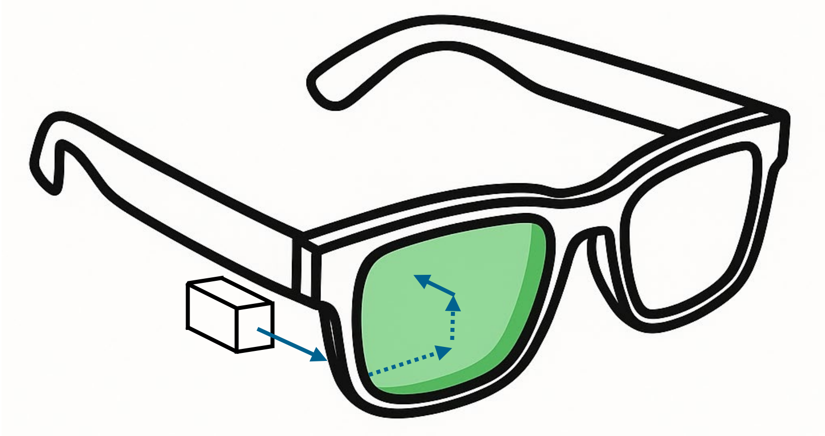
Introduction – AR Light Path

This tutorial demonstrates a lightguide-based AR display using diffraction gratings to couple light in and out of a transparent waveguide.

The waveguide is highlighted in green in the illustration on the right.

Light from a microdisplay enters the waveguide via an input grating and propagates horizontally through total internal reflection. A second grating redirects the light vertically, and an output grating projects it toward the user's eye.

This optical architecture enables the overlay of digital content onto the real-world view, fundamental to augmented reality. The system demonstrated here operates with monochromatic green light at a 532 nm wavelength.



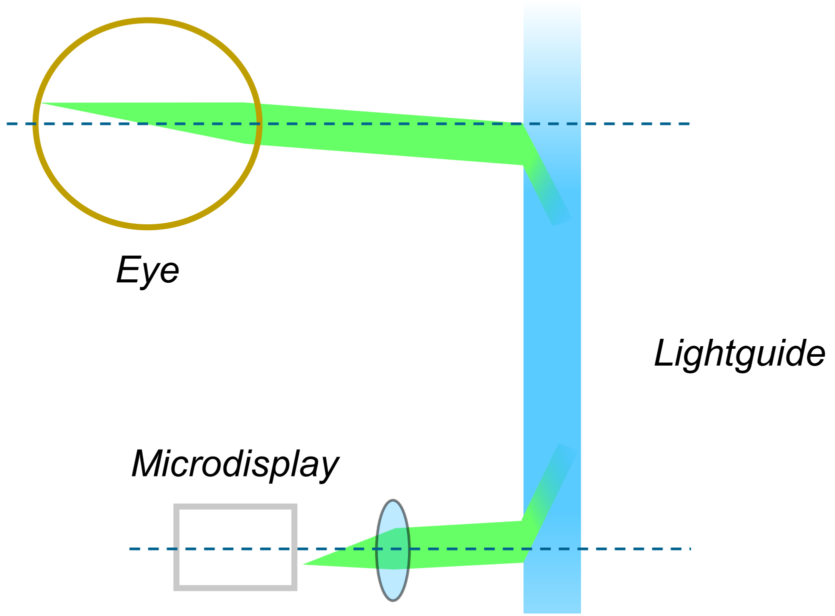
Introduction – Using Plane Waves in AR Simulations

This tutorial does not cover the microdisplay, nor the beam-shaping optics between the microdisplay and the input coupler. For our purposes, the microdisplay can be considered as a 2D array of green-light-emitting pixels. Each pixel emits spherical waves, which are transformed by the beam-shaping optics into collimated plane waves directed at specific angles toward the input coupler.

At the input coupler, we therefore simulate the light as a set of plane wave beams entering the lightguide at different angles. These beams propagate through the lightguide and are redirected toward the output coupler, where they exit again as collimated plane waves—effectively forming a mirror image of the input field.

The eye then focuses these beams onto the retina, forming the augmented image. It's important to note that the lightguide itself does not provide magnification. Any magnification or image positioning must be handled by the optics in front of the microdisplay.

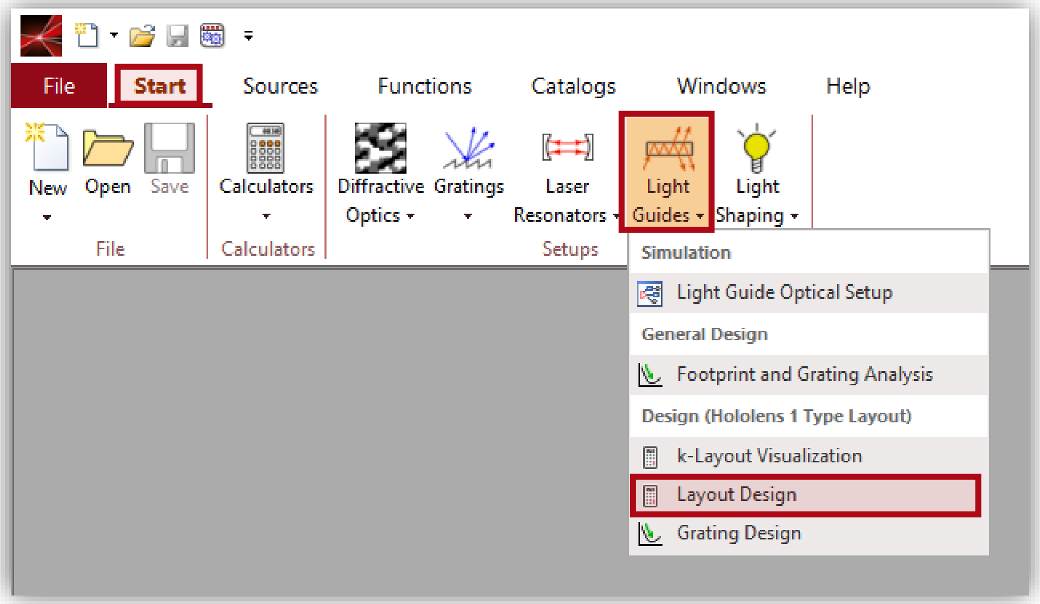
In the setup described here, the AR/MR image appears to be located at optical infinity due to perfect collimation. However, if the output is slightly divergent (i.e., not perfectly collimated), the eye would will focus at a finite virtual distance instead.



Layout Design – Incident Light

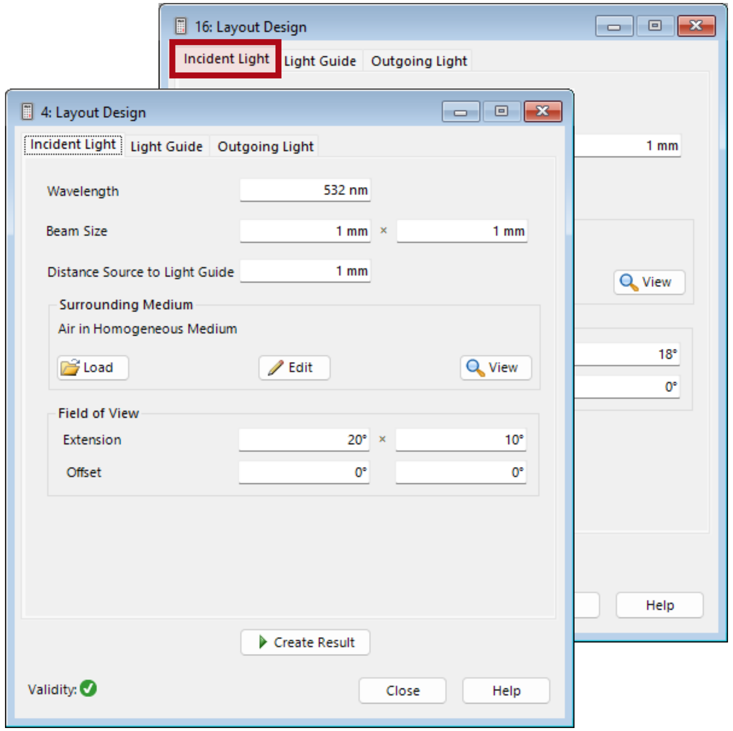
The AR/VR/XR package includes a wizard for simplified setup of HoloLens-like waveguides with two 1D beam expanders

- Launch *VirtualLab Fusion*
- In the *Start* ribbon, select *Layout Design* from the *Light Guides* drop-down menu



The wizard's default settings create a valid lightguide but we will adjust them for better insight

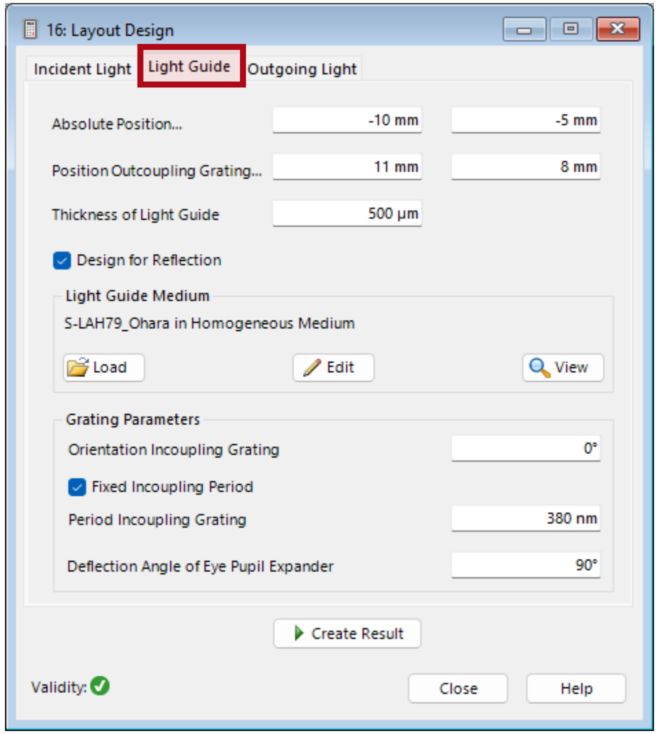
- Set *Distance Source to Light Guide* to 1 mm
- Set *Field of View* to 20° × 10°

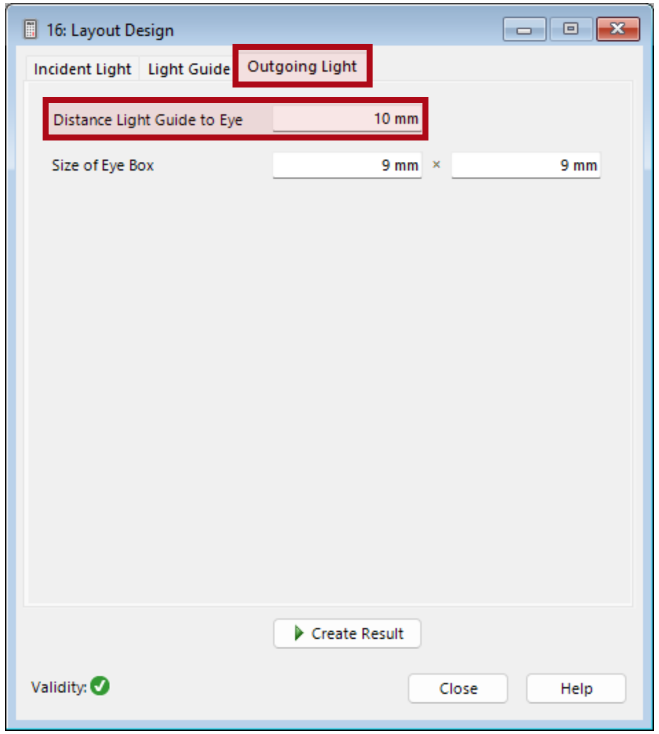


Layout Design – Light Guide & Outgoing Light

On the *Light Guide* tab, we will keep the default settings. However, note that this is where you can adjust parameters such as thickness, input coupler period, and the previously discussed internal deflection angle.

- In the *Outgoing Light* tab, set *Distance Light Guide to Eye* to 10 mm
- Leave *Size of Eye Box* at its default settings





Layout Design – Eyebox

In *VirtualLab Fusion* the *Size of Eye Box* defines the area in which the eye can move while still seeing the complete image.

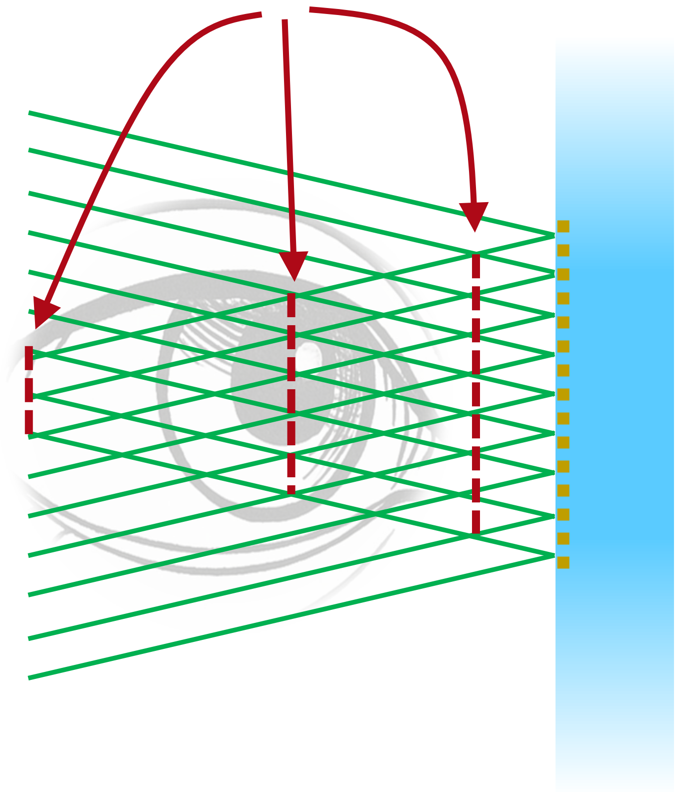
The target value is 9 mm × 9 mm at a distance of 10 mm from the output coupler.

As illustrated, the eyebox area decreases with increasing lightguide-eye distance.

Additionally, for a given lightguide layout, a larger *Field of View* (FOV) - the angular size of the AR image - also reduces the eyebox size.

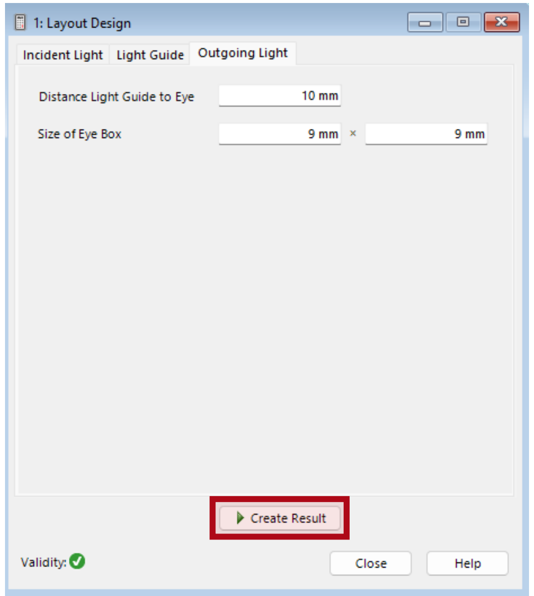
The FOV is determined by the microdisplay and the beam-shaping optics placed before the input coupler. In this sense, the FOV itself acts as a target value and is configured under the *Incident Light* tab.

Eye box sizes for different positions



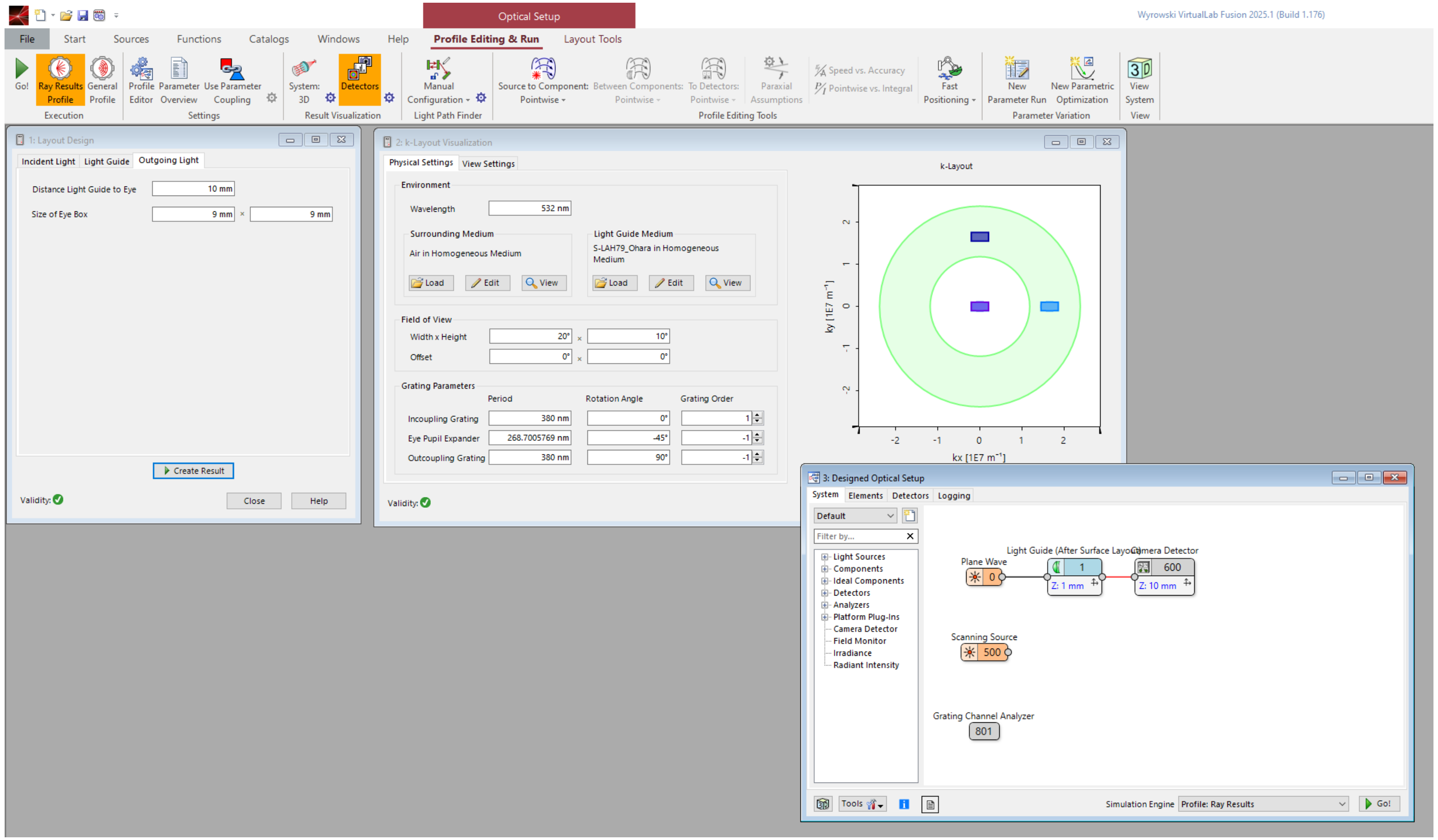
Layout Design – Create Result

- Click *Create Result*



Two more windows appear:

- *k-Layout Visualization*
- *Optical Setup View*

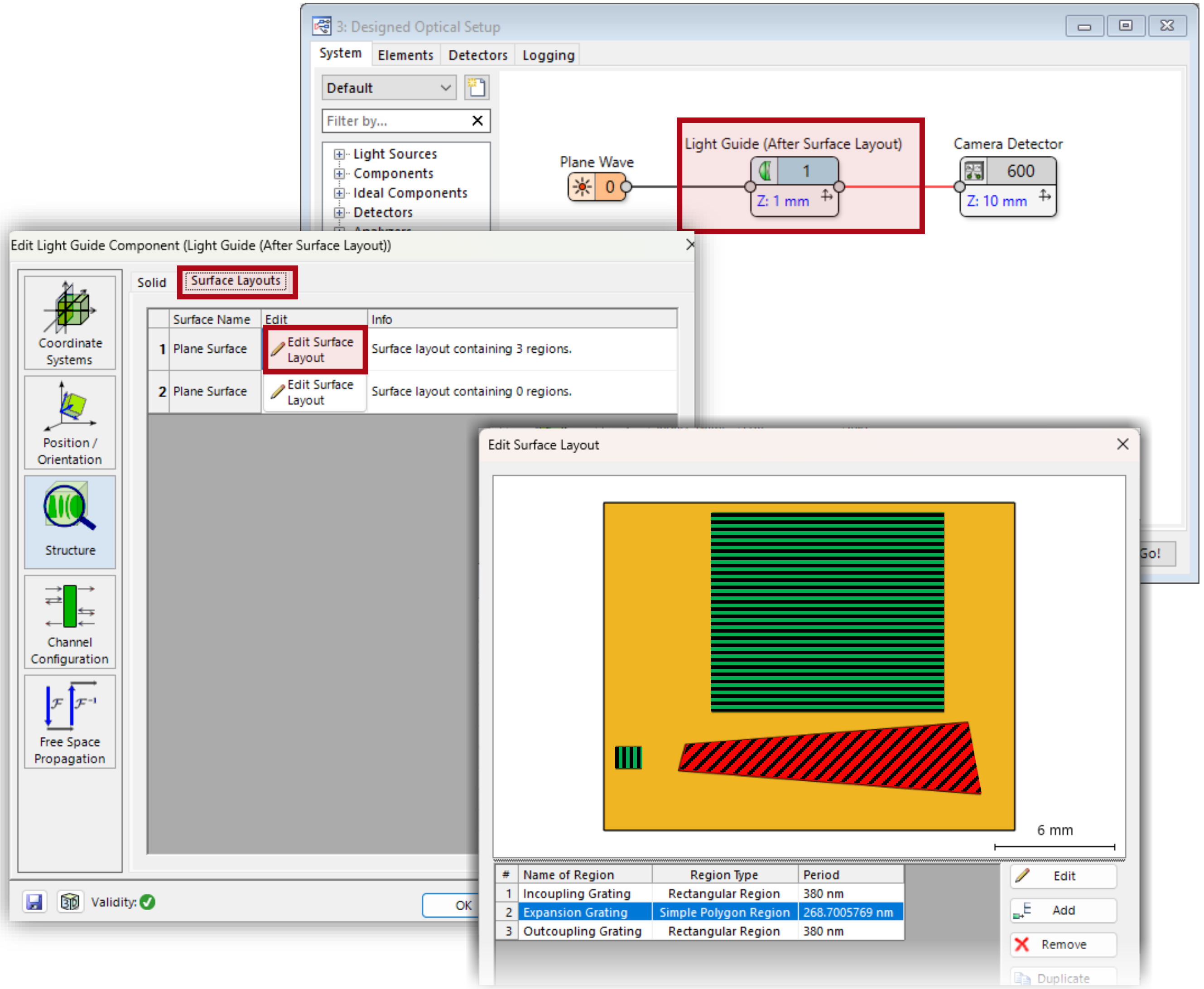


Check the Layout of the Gratings

- Double-click the *Light Guide* icon
- Select the *Surface Layouts* tab
- Click *Edit Surface Layout* of *Plane Surface* #1 (the surface facing the eye)

The *Edit Surface Layout* window displays a diagram of the grating regions, with the currently selected region (e.g., the second grating) highlighted in red.

In some design target combinations, the wizard may place overlapping gratings on the same surface, which is physically unfeasible. To prevent this issue, the current design employs a relatively small FOV.



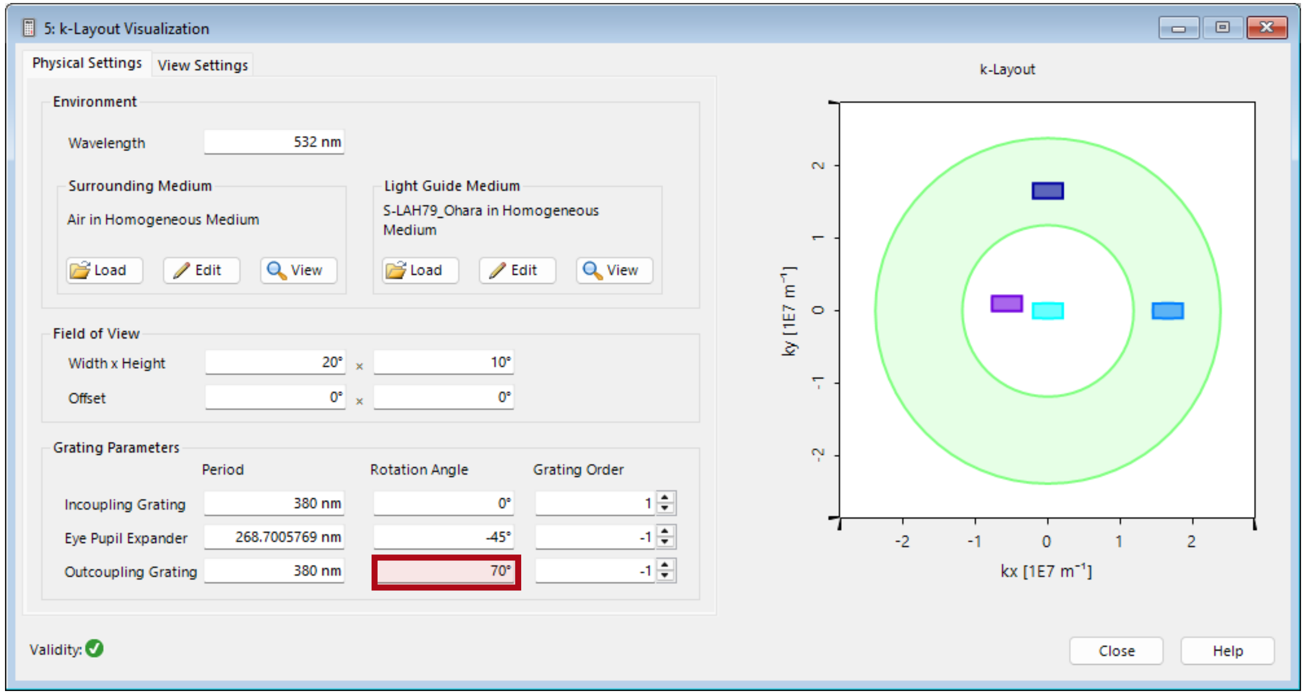
Note: The shadings indicating the grating orientations were added specifically for this tutorial.

Explore TIR Conditions with k-Layout Visualization

The *k-Layout Visualization* tool is an essential resource for rapidly assessing whether light within the lightguide is properly confined via total internal reflection (TIR). In the visualization, the green ring highlights the set of k-vectors that meet the TIR condition.

The present simulations employ plane waves, each defined by a specific k-vector. Although k-space analysis might seem unintuitive at first, it offers the most natural and effective framework for understanding light propagation in this context. The methodology will become clearer as we walk through each step of the process.

The diagram contains four data boxes, but two of them overlap. To improve visibility, set the *Outcoupling Grating: Rotation Angle* to 70°.



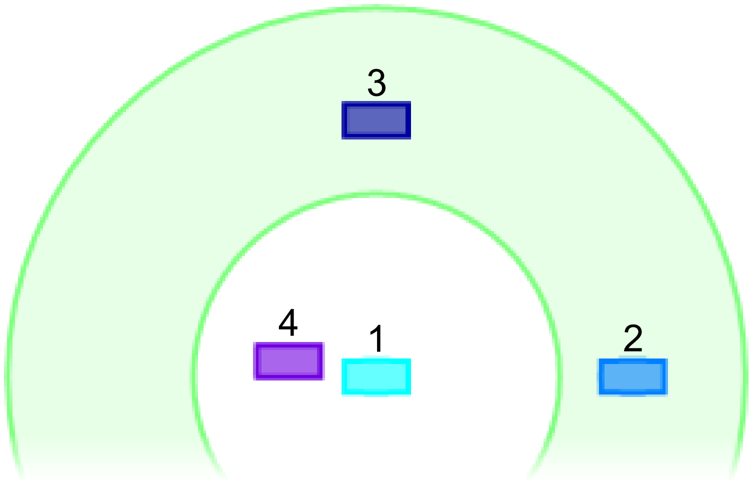
Note: K-Layout Visualization is an analysis tool only. Changes made here do not affect the setup

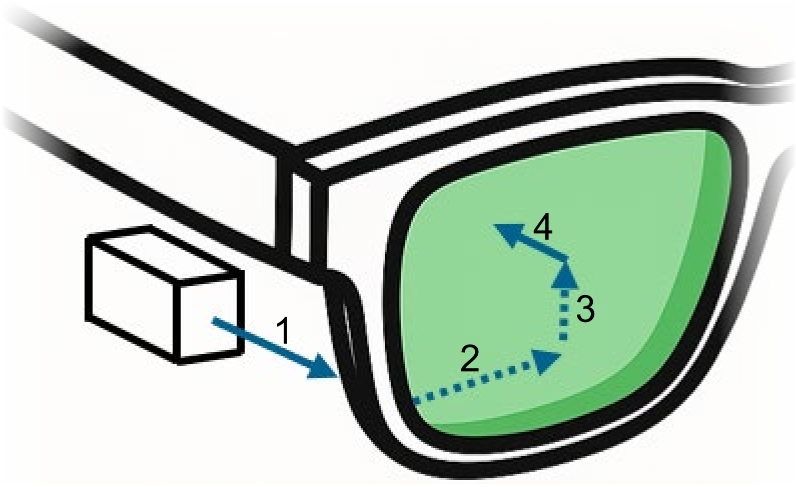
Identify Light Paths in k-Layout Visualization

The graphic shows the distribution of k_X and k_Y components at different positions in the optical setup. Since monochromatic light is used, the k-vector's magnitude remains constant across all plane waves in the same medium. However, k_X and k_Y vary with the propagation direction.

The light-blue box represents waves travelling towards the input coupler. A wave originating from the central microdisplay pixel has only a k_z component and therefore appears at the origin of the k-space plot. The box size reflects the range of input angles defining the FOV. Adjusting the FOV changes the box dimensions accordingly.

The diagram includes four such boxes, each corresponding to one of the four light path intervals in the setup, as indicated by the numbering in the illustrations on the right.



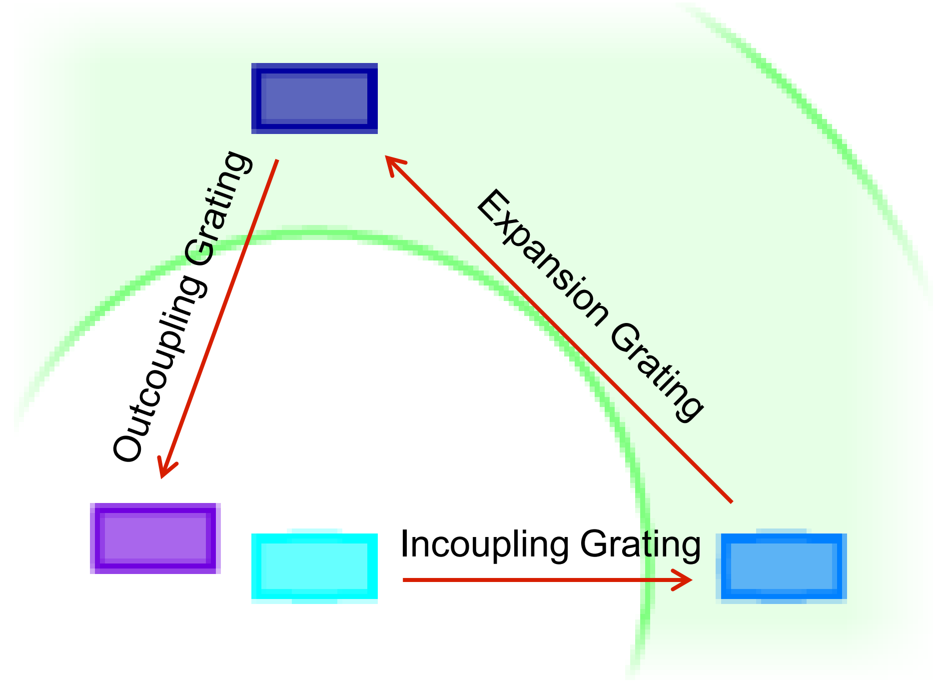


Explore How Gratings Manipulate Light Paths in k-Space

The gratings redirect the k vector by redistributing its k_x, k_y and k_z components. Diffraction into the desired orders appears as translations of the boxes in the diagram. With three gratings, there are three corresponding translations, as shown on the right.

The green ring indicates the condition for total internal reflection. The medium and dark blue boxes must stay within this ring. In the current setup, they do. But if the input coupler grating period is changed to 480 nm, the box moves outside the ring. (Tip: the translation equals the grating vector whose magnitude is 2π divided by the grating period.)

Total internal reflection does not affect k_x or k_y and therefore does not appear as a translation. The expansion grating is oriented at 45°, so the magnitude of the corresponding translation must increase by a factor of $\sqrt{2}$ in order to remain within the green ring. Consequently, the grating period must be smaller than that of the input coupler by the same factor.



Finally, the outcoupling grating should redirect the FOV back toward the center, or close to it.

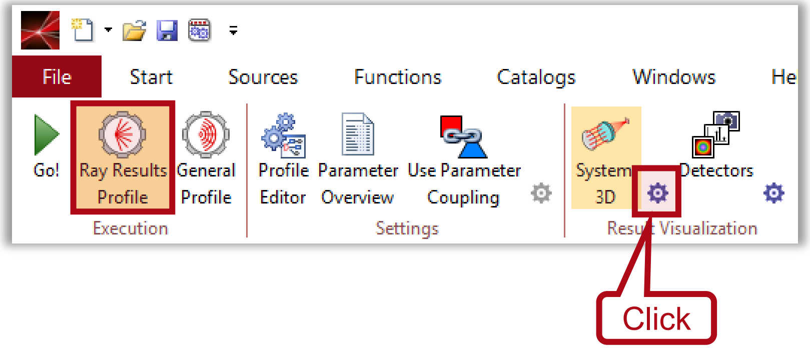
To learn more about this powerful tool, see the use case k-Domain Layout Visualization (“The Magic Circle”)

This tutorial will not use the tool further, so you may close it now.

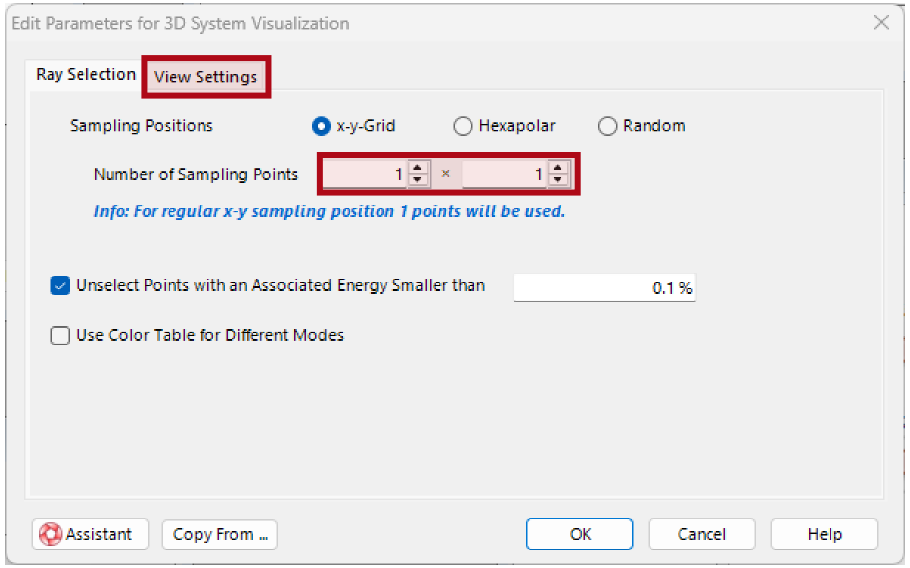
Beam Expansion – Setting Up

The beams entering the input coupler have diameters of only 1 mm. Transferring these beams to the output coupler without modification results in a very small eye box. To overcome this, the second and third gratings are used to expand the eye box. Ray tracing illustrates how this expansion is achieved.

- Close the *Edit Light Guide* dialog
- Close the *Layout Design* wizard
- Select *Ray Results Profile*
- Click the *cogwheel* icon next to *System: 3D*



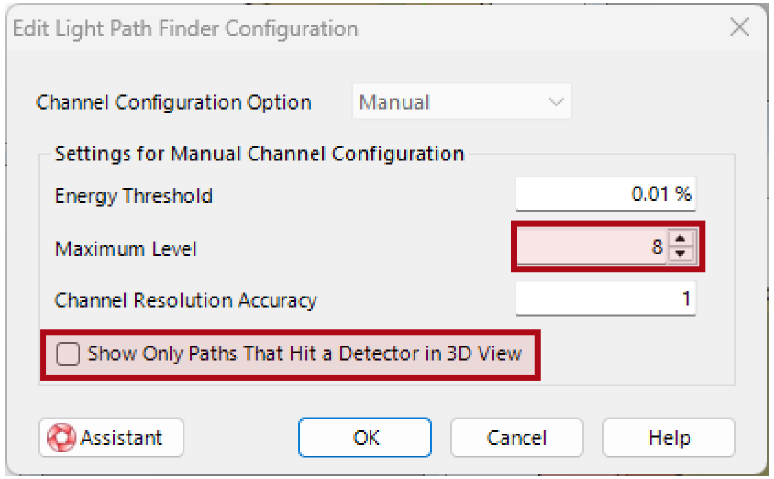
- Set *Number of Sampling Points* to 1 × 1
  This initializes the simulation with a single ray.



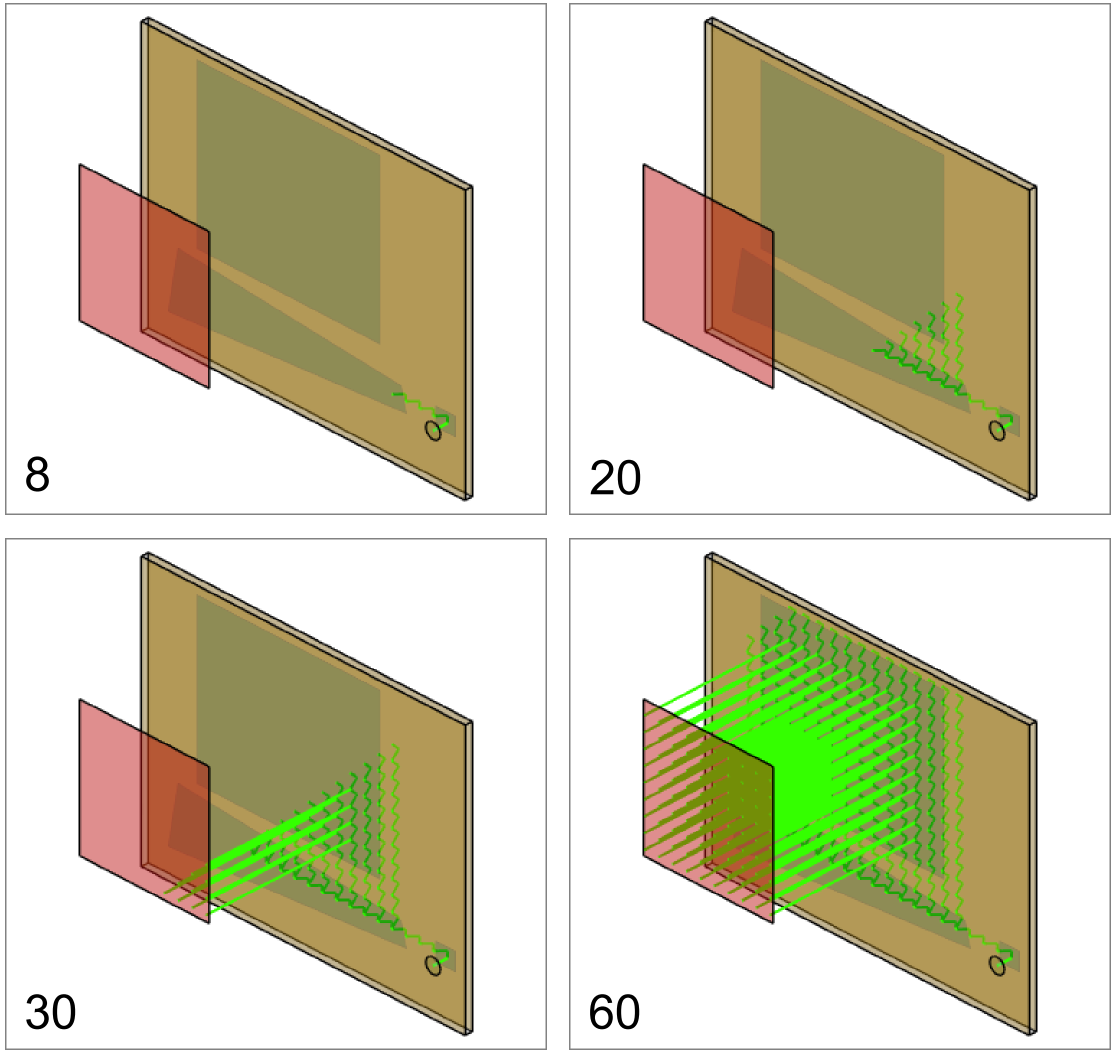
Tip: Use the *View Settings* tab to customize the appearance of the *Ray Results* plots. For the plots on the following pages *Background Color Gradient*, *Global Coordinate System*, *Tool Bar* and *View Cube* were deselected. Furthermore *Ray Thickness* was set to 2.

Beam Expansion – Follow the Rays

- Click the cogwheel icon in the *Light Path Finder*
- Set *Maximum Level* to 8
- Uncheck *Show Only Paths that Hit a Detector …*



- Run *Ray Results Profile/System: 3D*
- Repeat for *Maximum Levels* 20, 30 and 60
- Reset to default level 100



Note: The detector (in red) matches the eyebox size and is smaller than the output coupler.

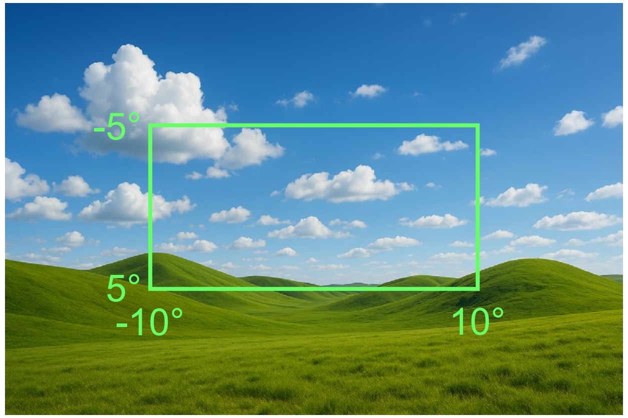
Discussion of Beam Expansion and FOV

The four simulations demonstrate how the beam expansion works. The polygon-shaped grating has a low diffraction efficiency, redirecting only a small fraction of the beam upward at each interaction. Most of the beam continues along its original path (zeroth order), allowing for repeated partial redirections. This process creates multiple adjacent copies of the beam along the horizontal axis. The output coupler uses the same principle along the vertical axis.

As a result, the eyebox is filled with closely spaced beam copies, ensuring that from any position within it, one or more beams will enter the eye.

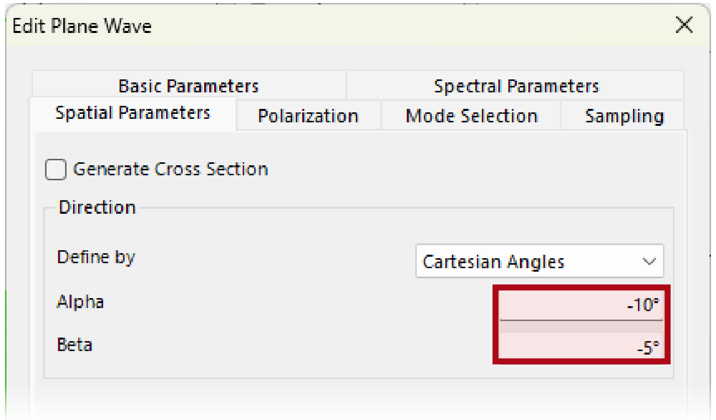
While the polygon-shaped grating is typically referred to as the *expansion grating*, it's important to note that the output coupler contributes equally to the overall beam expansion. Both elements are essential in forming the 2D array of beam copies that fill the eyebox.

So far, we have illustrated the beam expansion using a beam at 0°, which corresponds to a pixel located at the center of the field of view (FOV). To better understand the full shape and function of the expansion grating, it is helpful to consider beams corresponding to pixels near the corners of the FOV. This requires adjusting the input beam angle accordingly. It's important to remember that the FOV is defined as a total angular range – for example, a FOV of 20° spans from –10° to +10°. Selecting a pixel at the edge of the FOV means launching a beam at an angle near these extremes



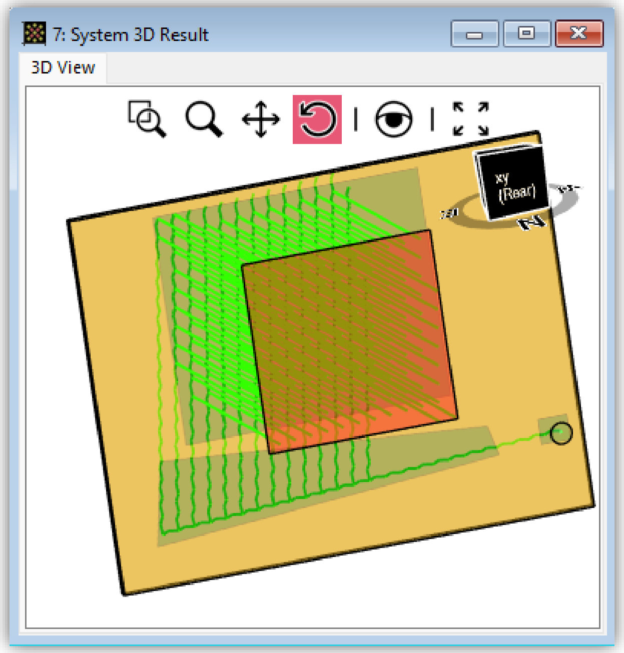
Understand the Grating Region Dimensions

- Double-click the *Plane Wave* source
- Set *Alpha* to -10°
- Set *Beta* to -5° and click *OK*



- Re-enable *Tool Bar and View Cube* (*cogwheel* next to *System: 3D*, then *View Settings*)
- Run the simulation
- Select the ⟲ tool and drag the mouse across the image to view the ray paths from various angles

Tip: Click directly on a face of the black cube to switch to a standard planar view.



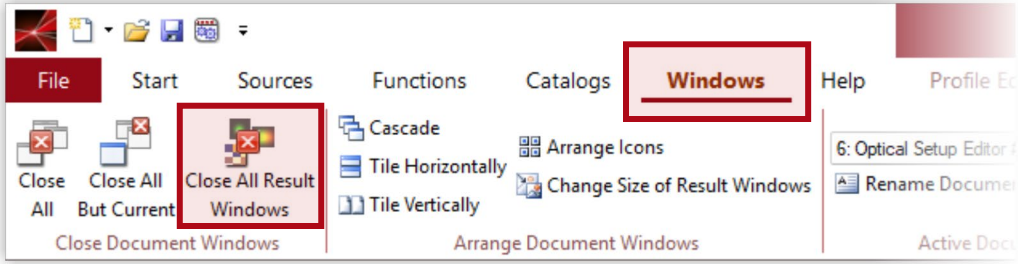
For further understanding, you may want to repeat this analysis with other values of *Alpha* and *Beta*.

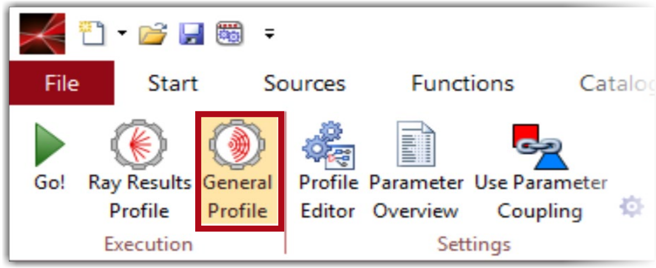
Conclusion: the four-sided polygon shape results from minimizing the expansion grating region while meeting design requirements. Likewise, the input and output couplers are the smallest possible rectangles.

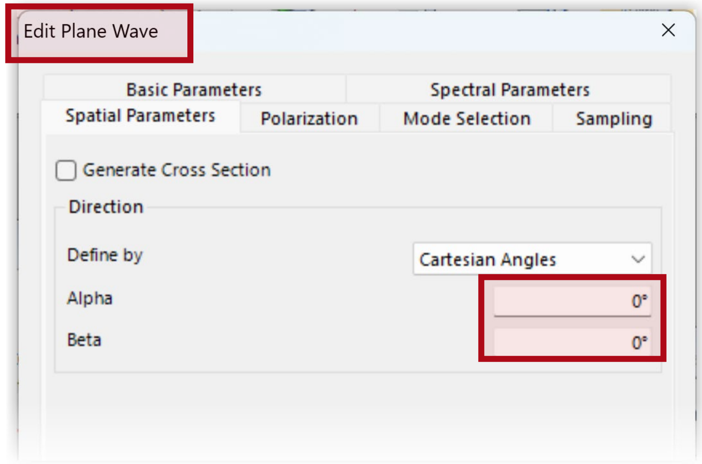
General Profile

Let us now move beyond ray tracing:

- Close all result windows
- Select the *General Profile*
- Set *Alpha* and *Beta* both to 0°
- Run the simulation





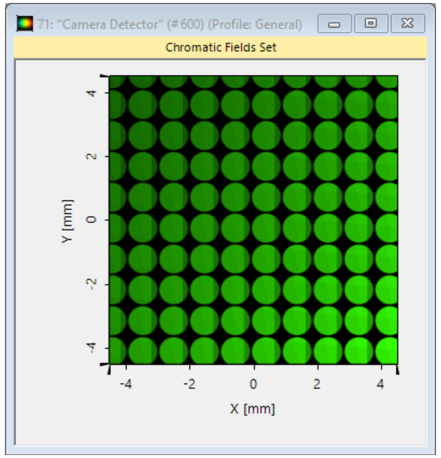


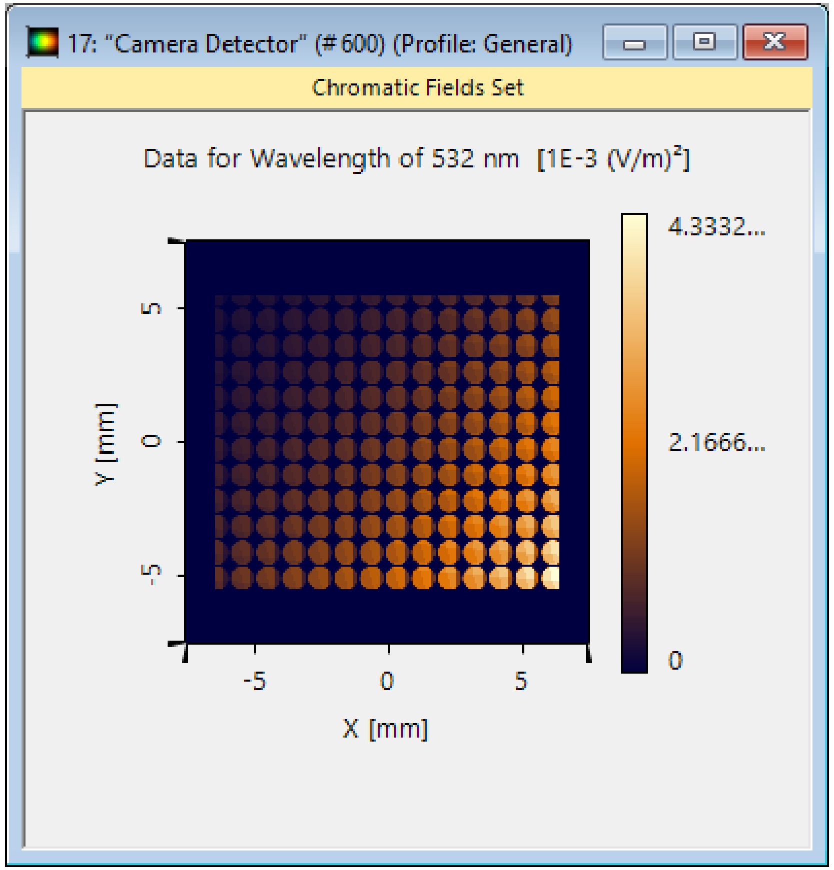
General Profile

The detector is currently limited to the eyebox, as defined in the setup wizard. To gain more insight, we'll enlarge the detector and switch to false color mode to better visualize brightness variations.

- Double-click the *Camera* object
- Set *Window Size* to 15 mm × 15 mm
- Change to *False Color: Midnight Sun*
- Run the simulation again

The simulation indicates that the beam copies decrease in brightness with increasing distance from the lower-right corner of the eyebox.

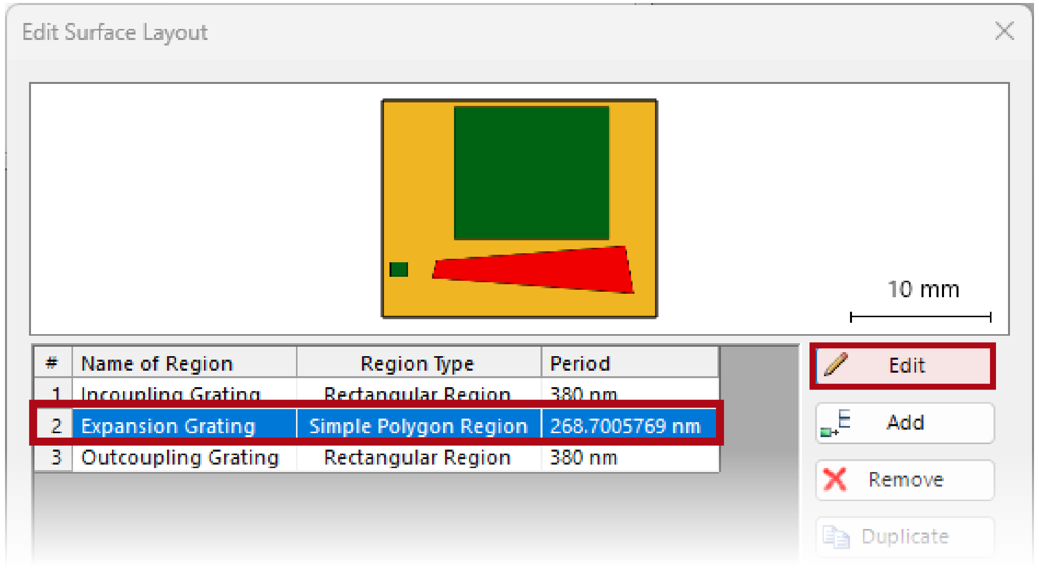




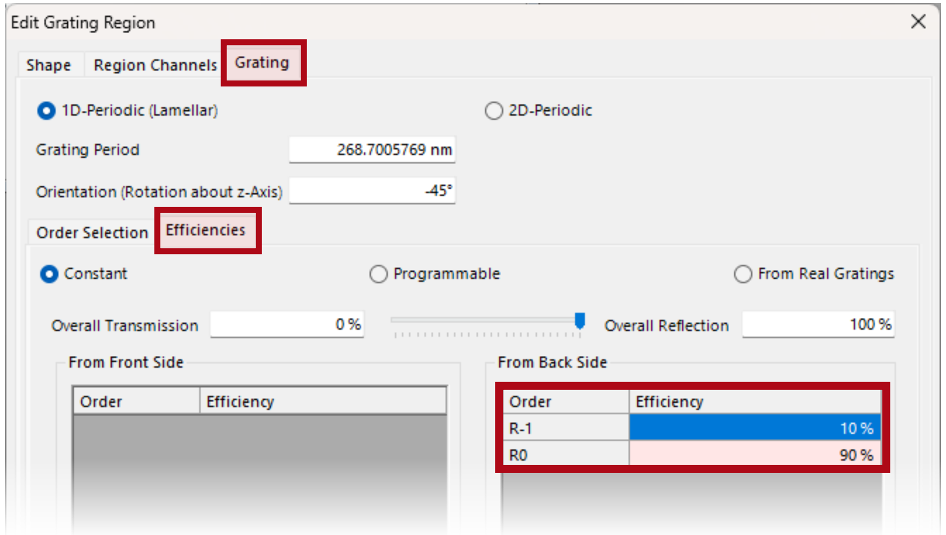
Brightness Variation Across the Eyebox

Let's examine the properties of the expansion grating:

- Open the *Edit Surface Layout* of the *Light Guide* component
- Select the *Expansion Grating*, then click *Edit*



- Click the *Grating* tab, then navigate to *Efficiencies*
- Review the values in the *Efficiency* table



We note that the diffraction efficiencies are constant. The same applies to the output coupler. The beams farther from the lower-right corner follow paths that interact more frequently with the gratings, and as a result, they become progressively weaker.

Beam Clipping

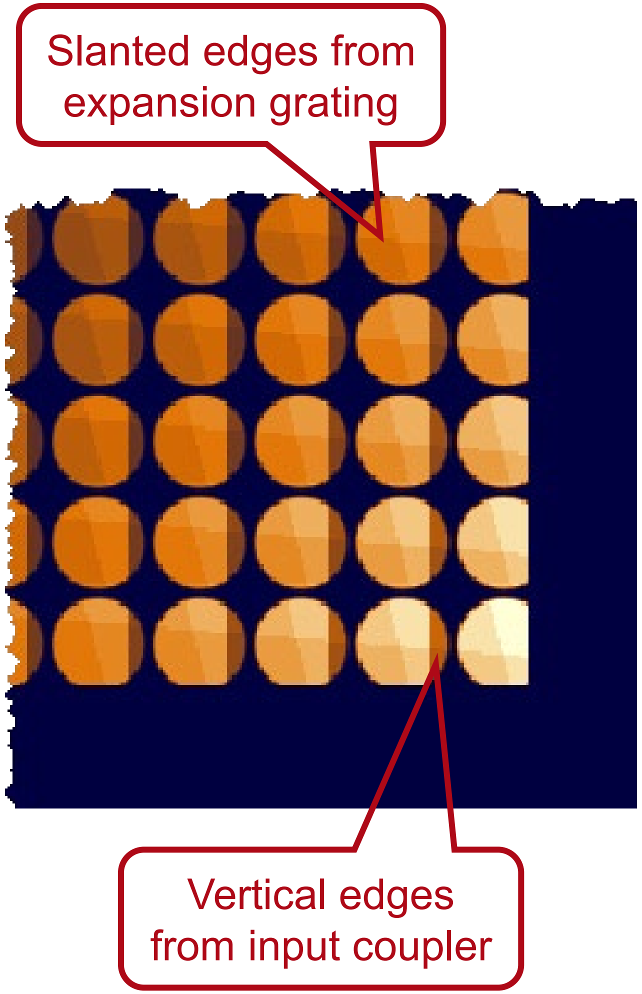
The boundaries of the regions cause partial beam clipping. When a beam partially overlaps a boundary, the portion outside the region undergoes 100% reflection due to total internal reflection (TIR), while the portion within the region experiences only partial reflection, since the grating's R_0 is less than 100%.

The outer edge of the current light distribution is defined by the size of the output coupler. The vertical edges arise from the beam partially hitting the inner side of the input coupler (R_0 = 50%) after its initial zigzag pass.

This can be verified by slightly adjusting the input coupler dimensions, which alters (or even removes) the dark edge. However, these dimensions are necessary to maintain the intended field of view (FOV) and the source-to-light-guide distance.

The expansion grating introduces two edges at slanted angles. The horizontal edge caused by the output coupler is barely visible in this plot.

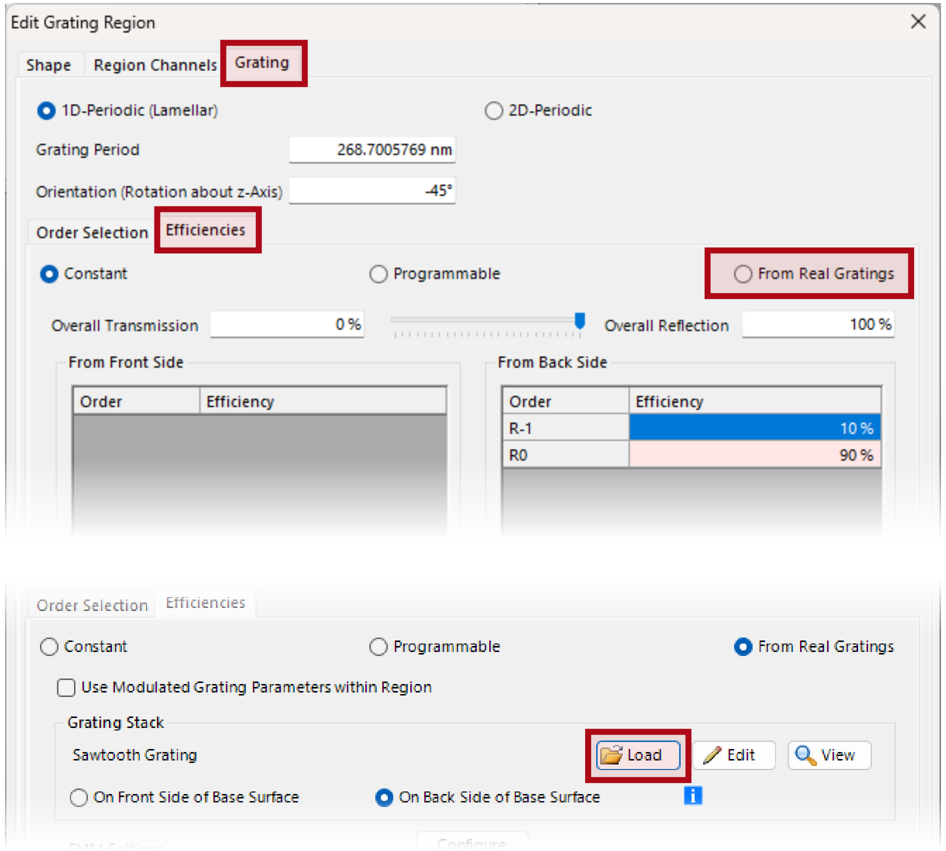
Clipping severity changes with input angle, and while it does not create visible edges in the AR image, it can lead to gradual brightness variations across the FOV.



Switch to Real Gratings

Our goal is to achieve more uniform brightness across the eyebox. A straightforward approach is to use expansion and output gratings with higher zeroth-order efficiencies (e.g. R_0 = 95%). However, this reduces overall brightness, lowering the efficiency of the lightguide system. A more effective strategy involves varying grating efficiencies across the region. The use case *Optimization of Lightguide with Continuously Modulated Grating Regions* demonstrates how to apply the uniformity detector and automated optimization to determine optimal grating parameters.

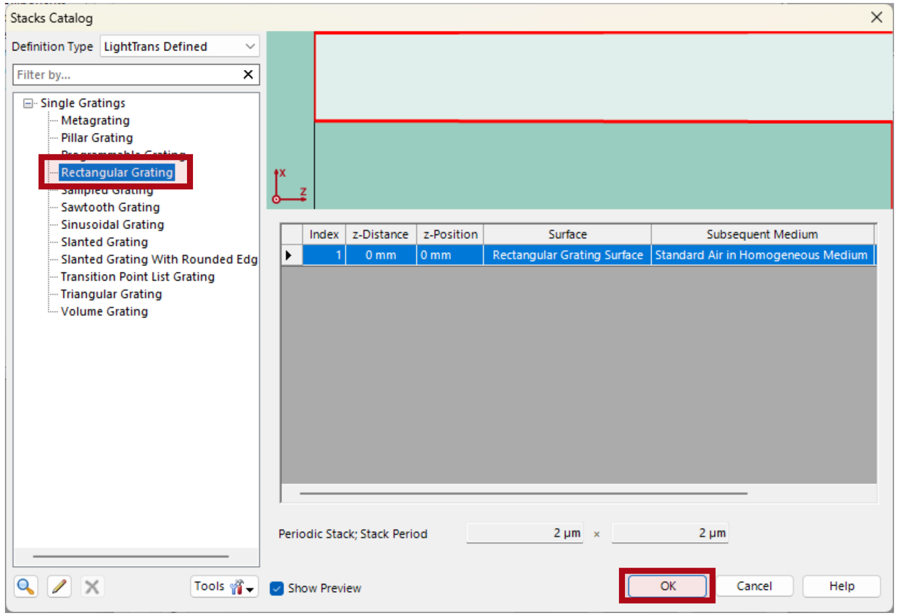
In this tutorial, we will also work with real gratings, but manually adjust their design to deepen understanding and better prepare for advanced use cases.



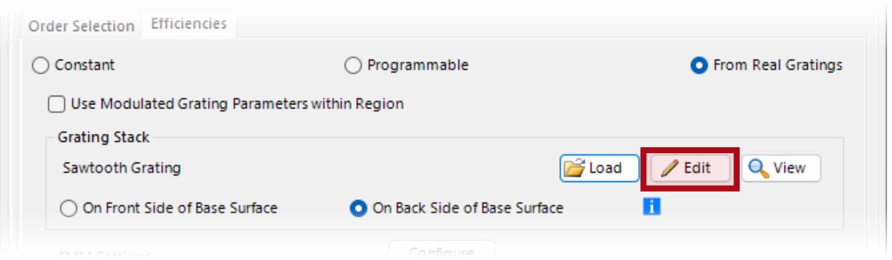
- Edit the *Expansion Grating*
- Under *Efficiencies* - Select *From Real Gratings*
- Click on *Load*

Load and Edit a Rectangular Grating

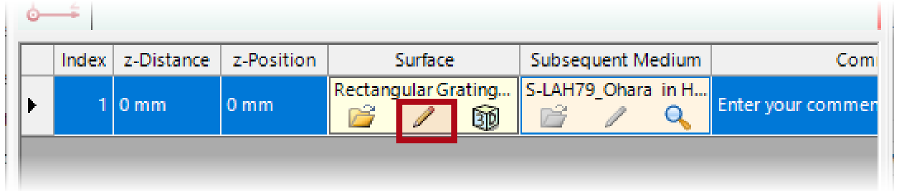
- Select *Rectangular Grating* and click *OK*



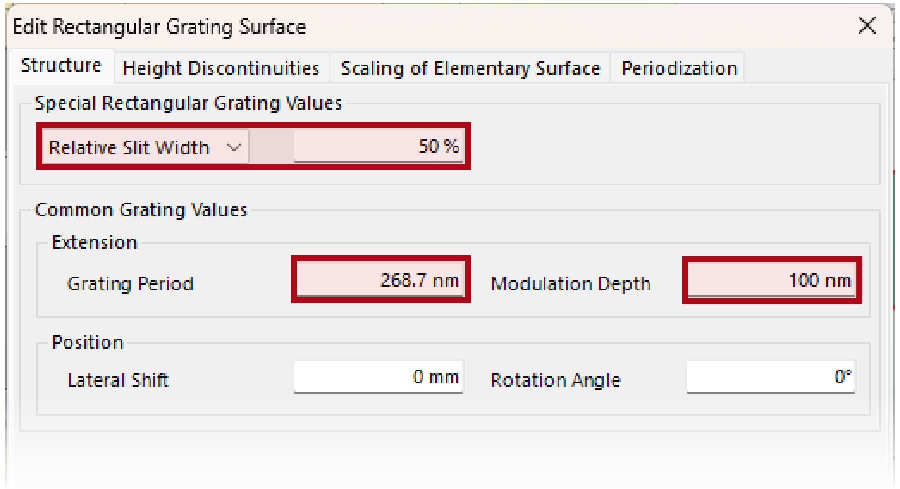
- Click on *Edit*



- Click the *pencil* symbol



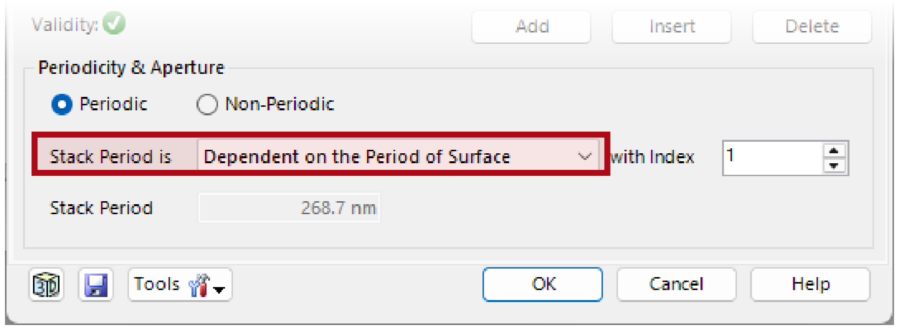
- Switch to *Relative Slit Width: 50%*
- Set the *Grating Period* to 268.7 nm and the *Modulation Depth* to 100 nm



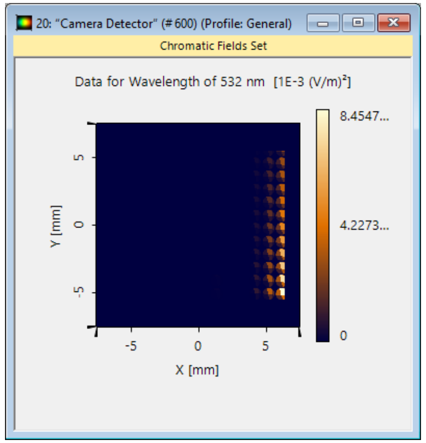
- Click *OK*

Change the Modulation Depth of the Grating

- Select *Stack Period is Dependent on the Period of Surface*



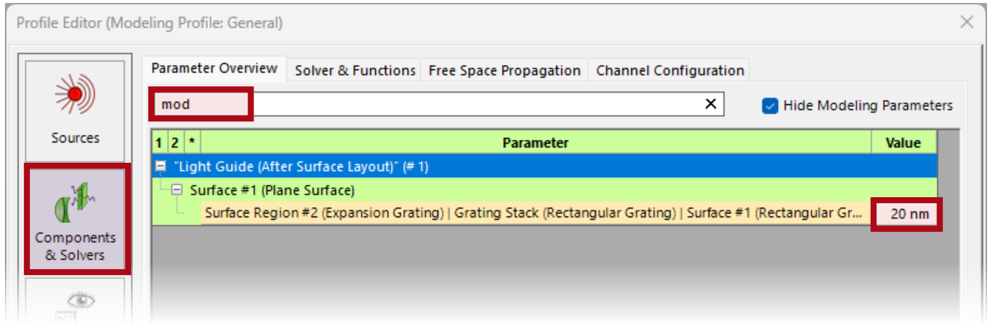
- Close all dialogs by clicking *OK* in each
- Run the simulation



Note: The rapid brightness drop-off in the horizontal direction. This suggests excessive diffraction at the expansion grating and a too-low R_0. Reducing the *modulation depth* can improve this.

- Open the *Profile Editor*

- Select *Components & Solvers*
- Start typing *modulation* - note that *mod* is sufficient.
- Set the *Value* to 20 nm

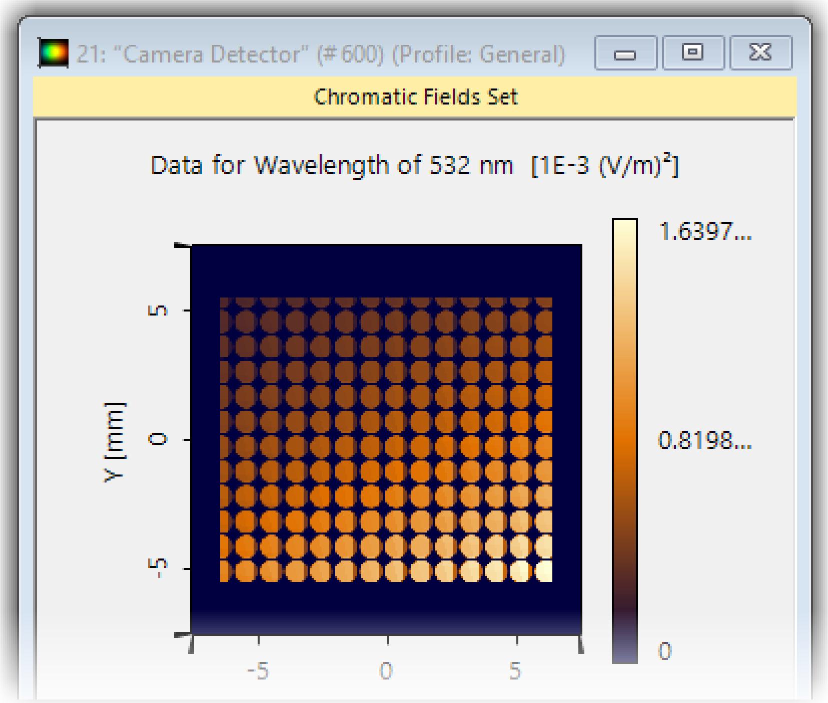


Divide the Expansion Grating into Segments

Run the simulation and observe that the brightness drops by about 50% in the horizontal direction, indicating a high R_0, likely around 90%.

However, compared to the initial design with an ideal grating, the overall efficiency has decreased by roughly 50%.

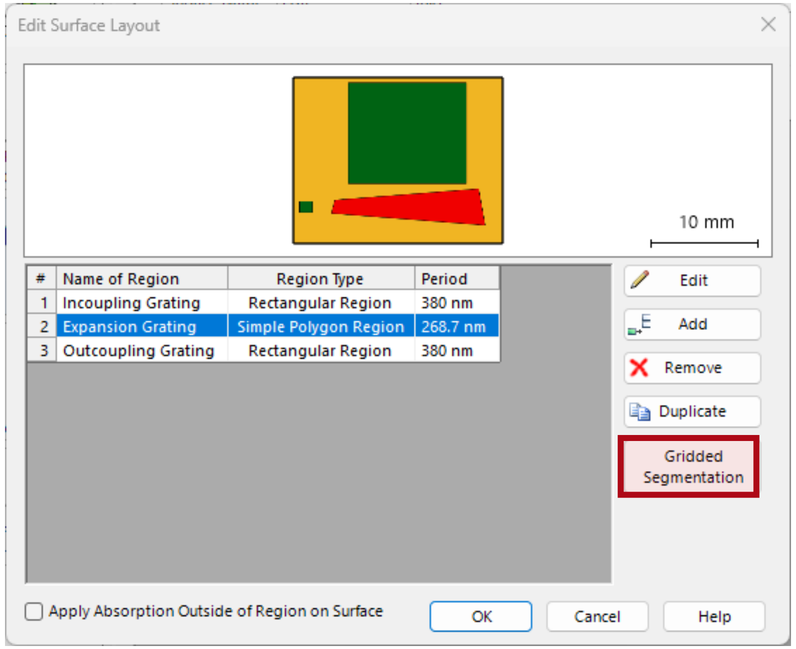
This suggests that R_{-1} is not approximately 10% as intended, but closer to 5%, with the remaining light lost to unwanted diffraction orders.



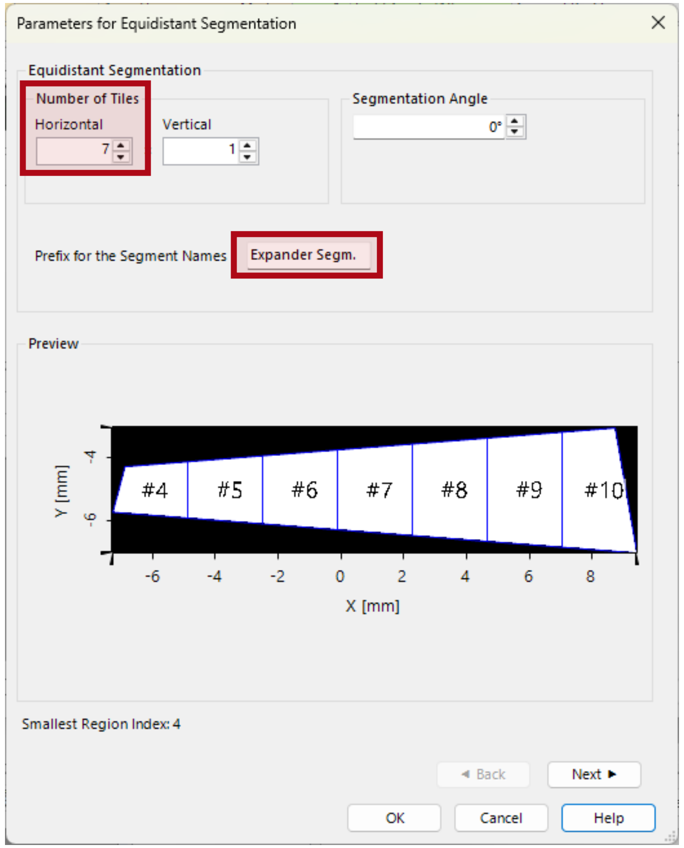
Divide the Expansion Grating into Segments

Next, divide the *Expansion Grating* into multiple smaller segments and gradually vary the modulation depth.

- Select the *Expansion Grating*
- Click *Gridded Segmentation*

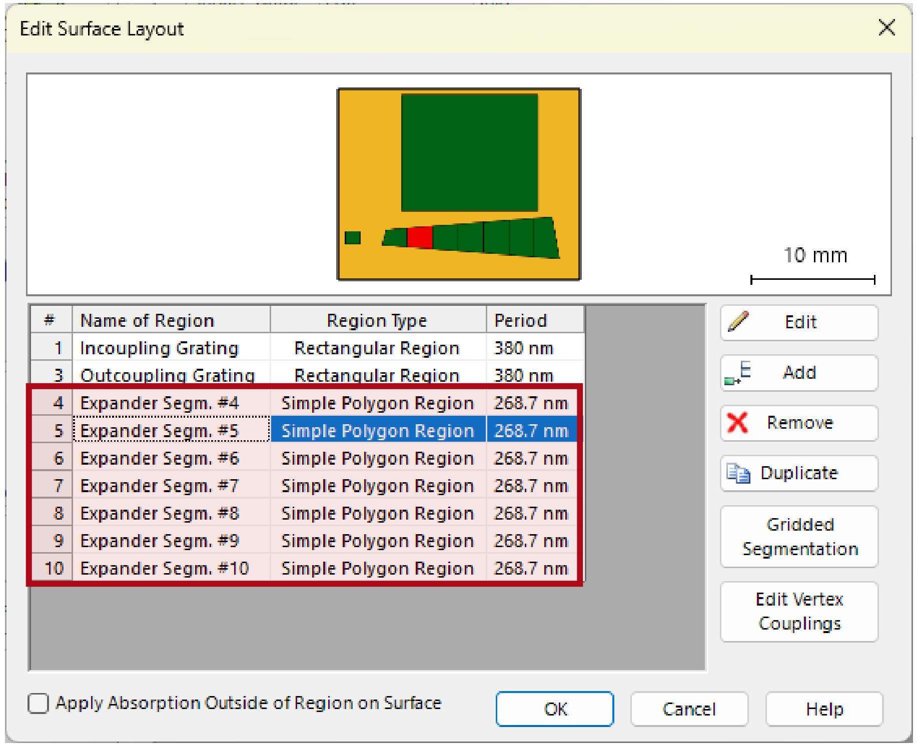


- Set *Number of Tiles: Horizontal* to 7
- Enter a descriptive segment name
- Click *OK*



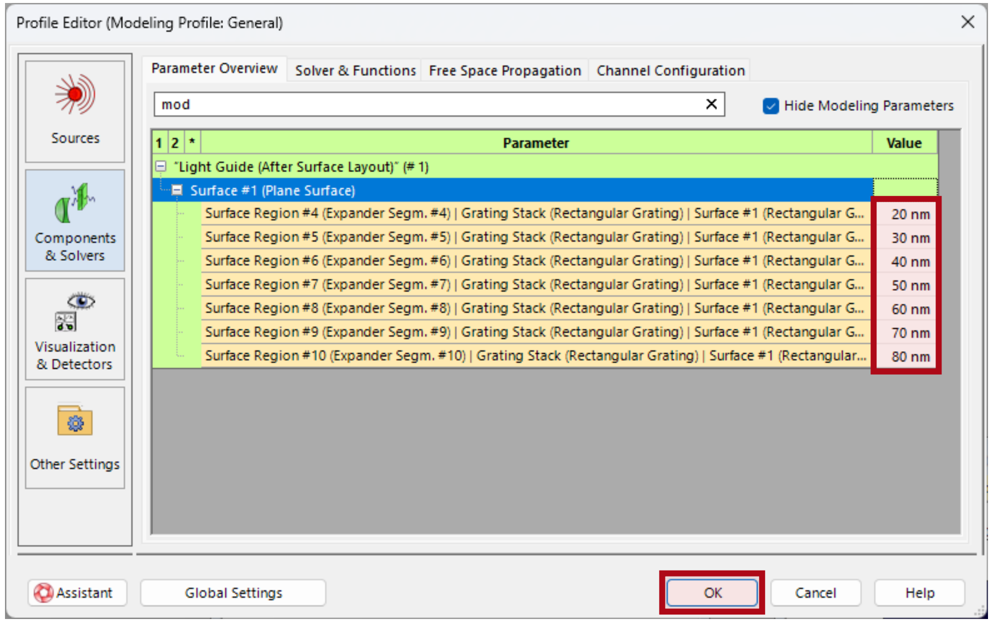
Vary the Modulation Depth Across the Expansion Grating

Observe the segmentation of the expansion grating.



- Close all dialogs by clicking *OK* in each
- Open the *Profile Editor*

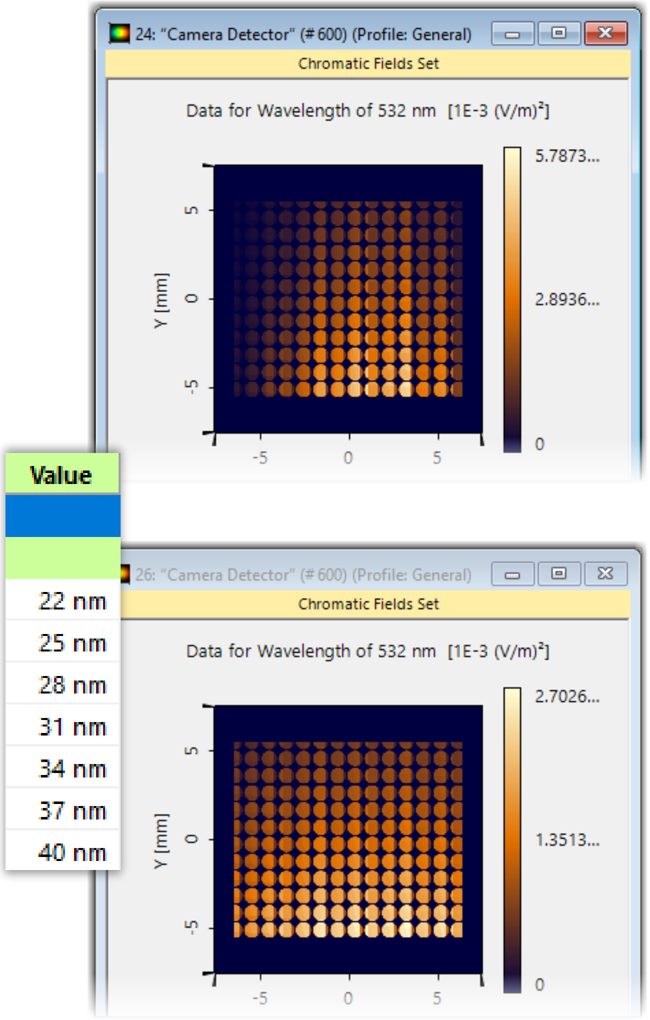
- Keep the first segment's modulation depth at 20 nm
- Increase by 10 nm for each following segment
- Click *OK*



Final Design of the Expansion Grating

Run the simulation and observe that the brightness in the horizontal direction initially increases, then decreases. Using smaller steps and a slightly higher starting value may result in a more even distribution.

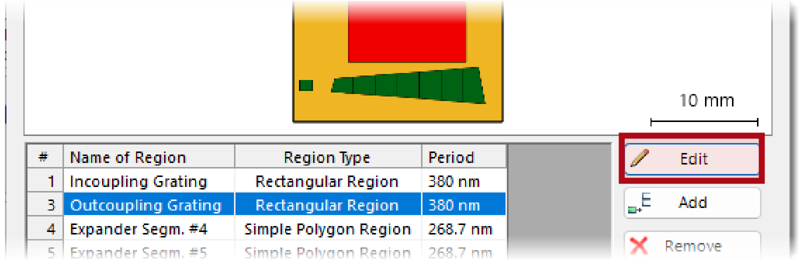
- Start at 22 nm
- Use increments of 3 nm
- Run the simulation



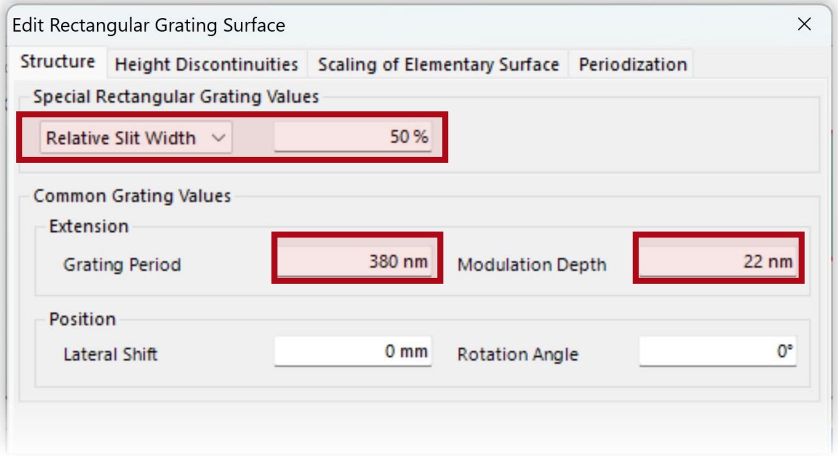
Final Design of the Expansion Grating

Let us accept this result and move on to the output coupler:

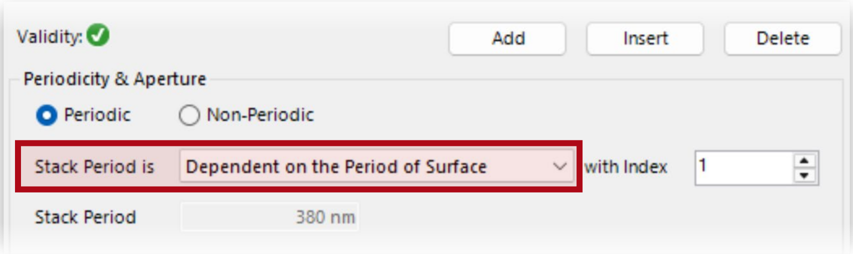
- Select the output coupler and click *Edit*



- For the grating efficiences, choose *From Real Gratings* and load a rectangular grating
- Edit the rectangular grating:
    - Set *Relative Slit Width* to 50%
    - Set *Grating Period* to 380 nm
    - Set *Modulation Depth* to 22 nm
    - Click *OK*

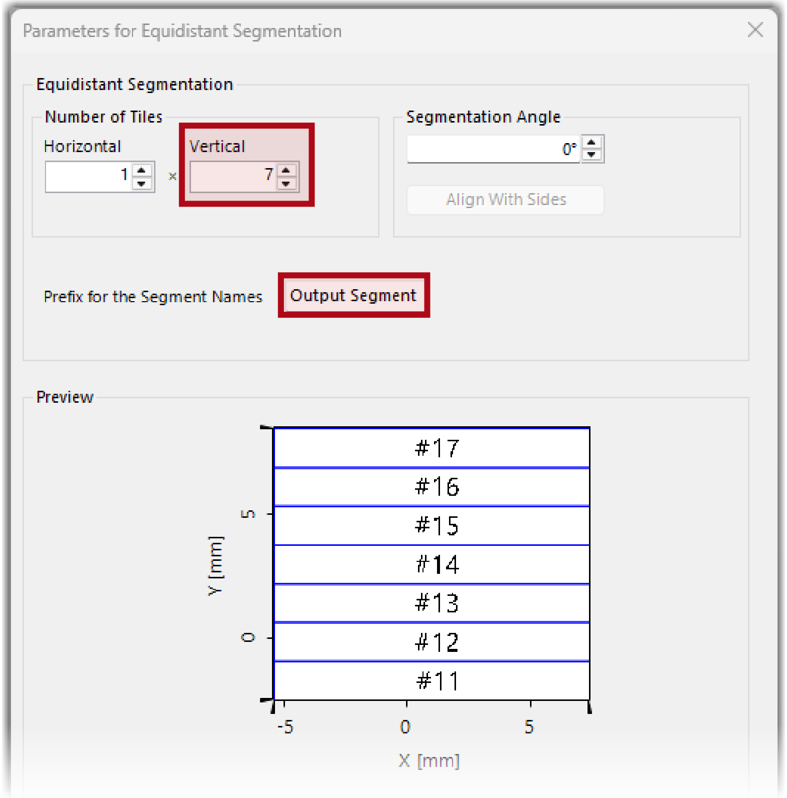


- Select *Stack Period is Dependent on the Period of Surface*
- Click *OK* twice

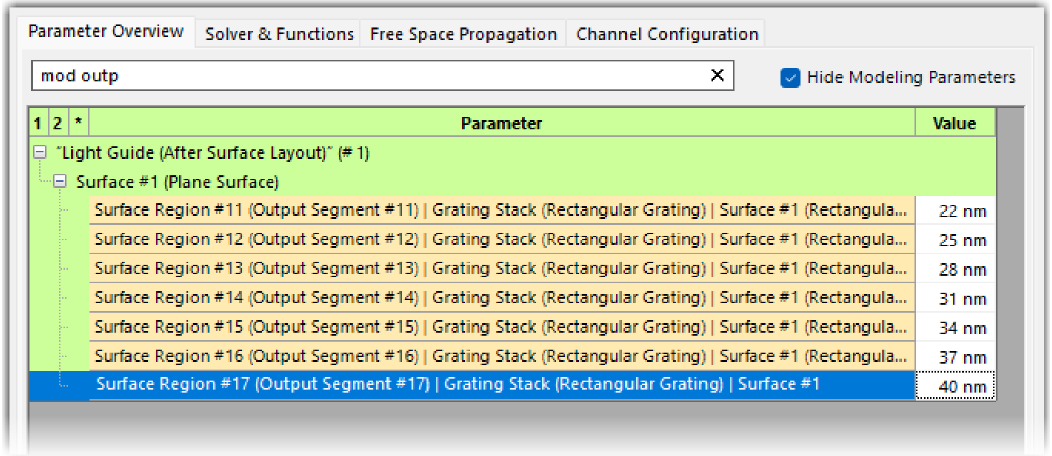


Divide the Output Coupler into Segments

- Go to *Gridded Segmentation*
- Set *Number of Tiles: Vertical* to 7
- Rename to *Output Segment*



- Open the *Profile Editor* and enter: *mod outp* in the search bar
- Set the *Values* to 22 nm, 25 nm, etc.

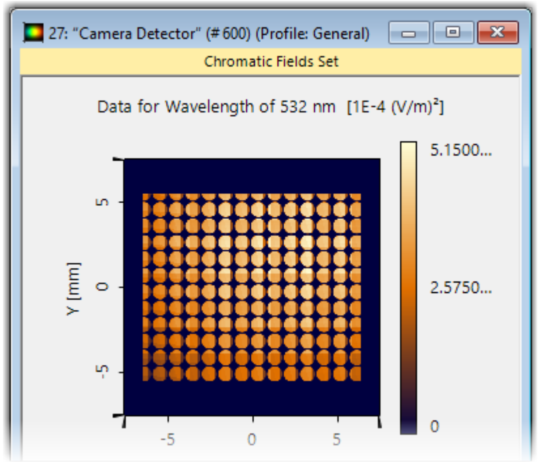


- Run the simulation

Divide the Output Coupler into Segments

Run the simulation and observe the brightness distribution, which suggests the need for higher modulation depths.

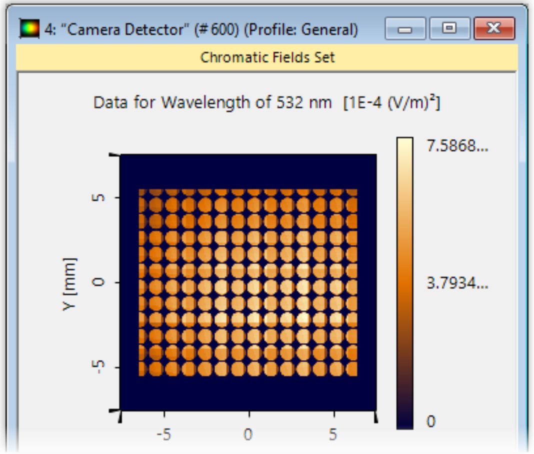
Since the period has increased by a factor of $\sqrt{2}$, scale the modulation depths accordingly to maintain the aspect ratio.



- Set the values according to the table below and run the simulation

Value
31 nm
35 nm
40 nm
44 nm
48 nm
52 nm
57 nm

Now display the result again,
but limited to the 9 mm × 9 mm eyebox and place it side by side with the result from the original design to allow direct comparison.



Final vs. Original Design

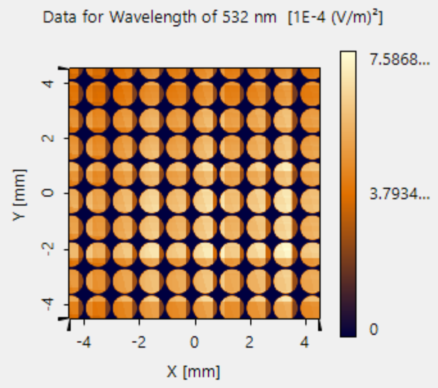
The light distribution across the eyebox is now significantly more uniform.

However, using real gratings has reduced overall efficiency. The original design assumed ideal gratings with a reflectivity of R_0 = 90% and 10% of the light directed into the desired diffraction order.

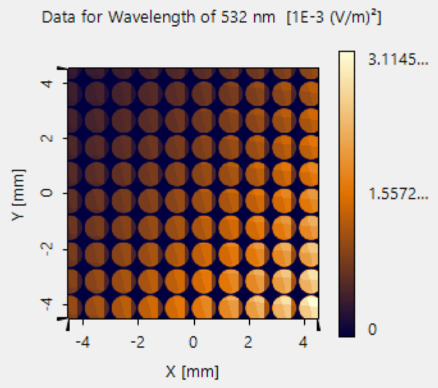
In practice, rectangular gratings scatter a notable portion of light into unwanted diffraction orders.

For example, if 5% is lost this way, efficiency in the desired order could drop from 10% to 5%, a twofold reduction per grating.

This highlights the potential for improvement by refining the grating design, such as exploring non-rectangular profiles or optimizing the relative slit width.



Real grating with varied efficiences



Ideal grating with constant efficiences

Next Steps in AR/VR Lightguide Design

Designing an effective light guide is a complex task that involves balancing multiple optimization goals. For each angle, we aim to:

- Minimize diffraction into undesired orders
- Maximize total efficiency
- Ensure uniform brightness across the eyebox

When considering the entire field of view (FOV), additional goals include:

- Achieve uniform brightness across the FOV
- Maximize the field of view
- Preserve the clarity of the real-world scene

While balancing these factors requires careful trade-offs, VirtualLab Fusion supports this process with powerful numerical tools for grating analysis and flexible optimization capabilities.

As an example, diffraction efficiency lookup tables can be precomputed for a defined parameter space, reducing computational cost in iterative design processes and enabling integration into automated workflows.

Further tutorials and advanced use cases are available via the Diffractive Lightguides section on our website.

Conclusion

Our goal was to introduce the fundamentals of lightguide design for AR/MR glasses.

We examined the structure and function of three key grating regions: the input coupler, the expansion grating, and the output coupler. The expansion grating replicates the beam horizontally, while the output coupler does so vertically - positioning multiple beam copies to fill the entire eyebox, thus ensuring the AR image remains visible across a range of eye positions.

To achieve uniform brightness, we tuned the efficiency of rectangular gratings through modulation depth adjustments. While effective, further refinements - like non-rectangular profiles or narrower slits - hold promise for even greater performance.

AR/MR technologies illustrate the transition of state-of-the art optical systems from niche applications to broader consumer markets.

Addressing the design challenges in this domain requires advanced modeling capabilities. VirtualLab Fusion provides the simulation environment necessary to meet these technical requirements.

We hope you found this tutorial valuable and invite your feedback, which helps us refine future materials and better address the needs of the optics community.

info@lighttrans.com

Document Information

title	Getting Started with AR/MR Lightguide Design
document code	TUT.0450
document version	1.0
required packages	AR/VR/XR Package / Grating Package
software version	2025.1 (Build 1.176)
category	Tutorial
further reading	- Diffractive Lightguides