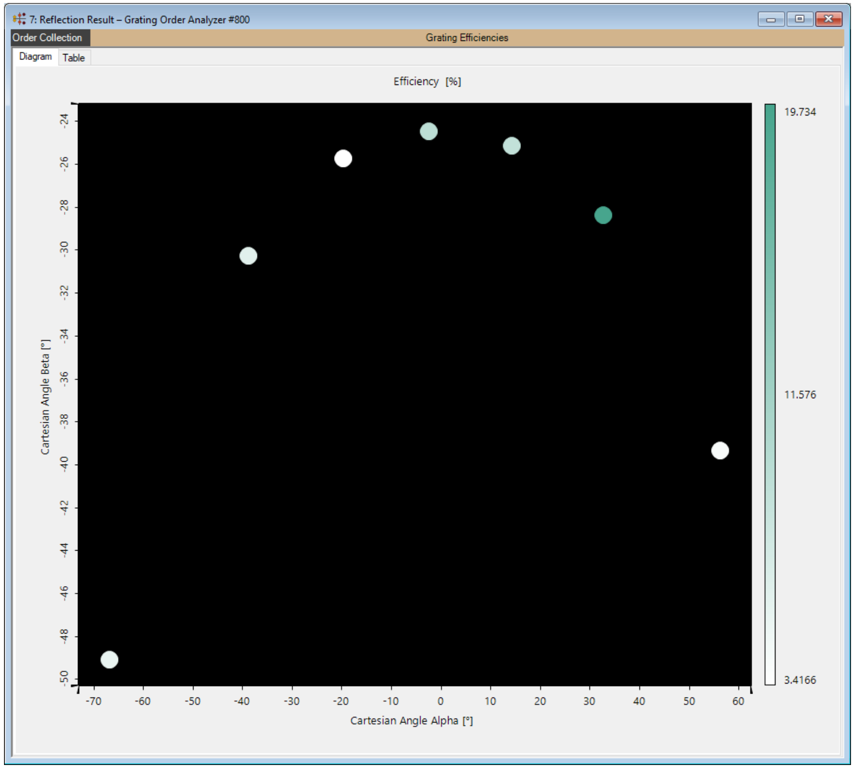
# Advanced modelling of gratings in VirtualLab software

Site Zhang, development engineer
Lignt Trans

# *Content*

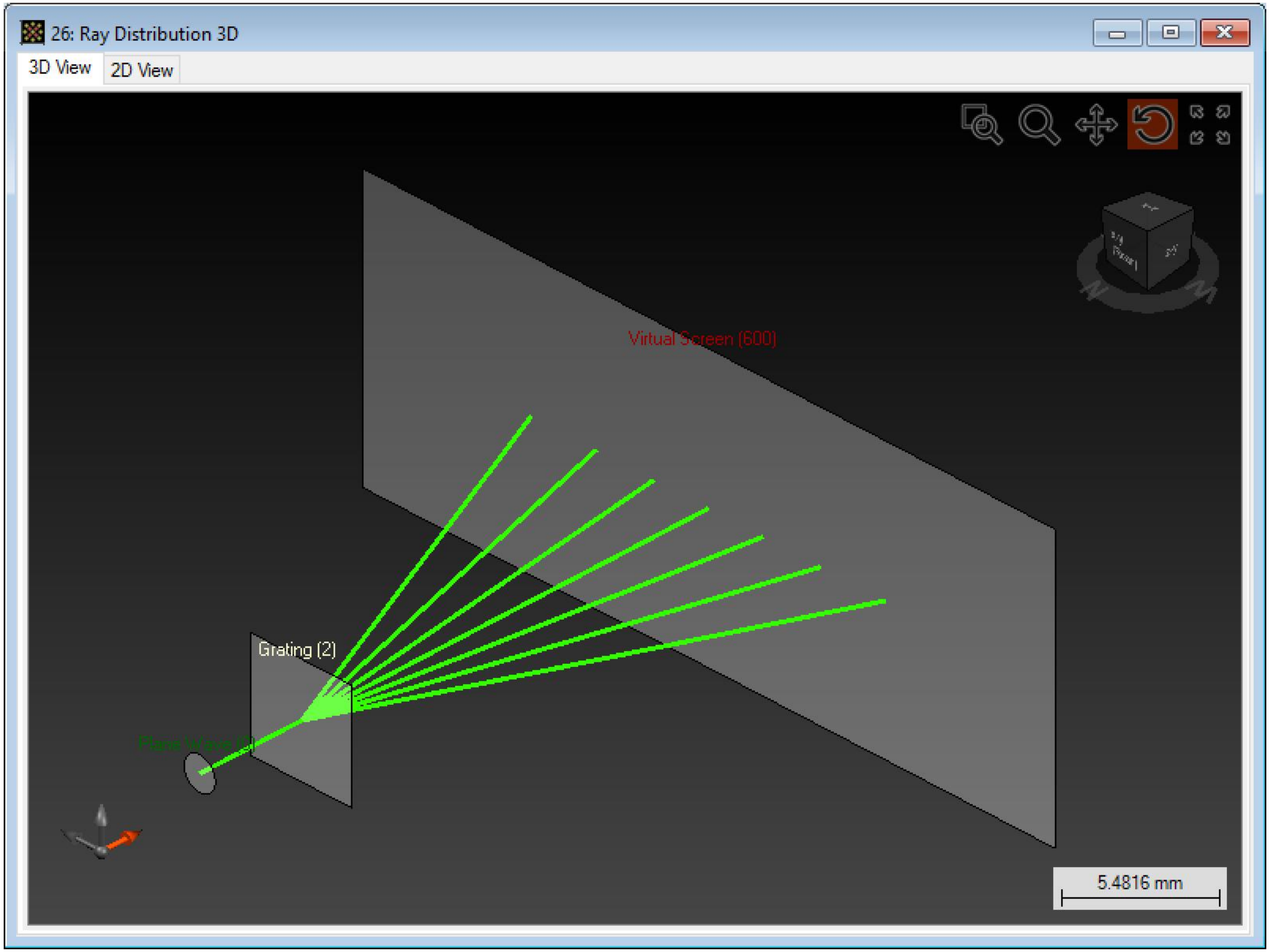
# Grating Order Analyzer

# Abstract




The analysis of the diffraction efficiencies of gratings is the typical modeling task with gratings. The efficiencies follow from the Rayleigh coefficients. Both quantities are given for each of the diffraction orders of a grating.  VirtualLab Fusion enables the calculation of efficiencies and Rayleigh coefficients by the fully vectorial Fourier modal method (FMM). This is done by the Grating Order Analyzer, which can display the efficiencies and Rayleigh coefficients of the distinct orders in various ways.

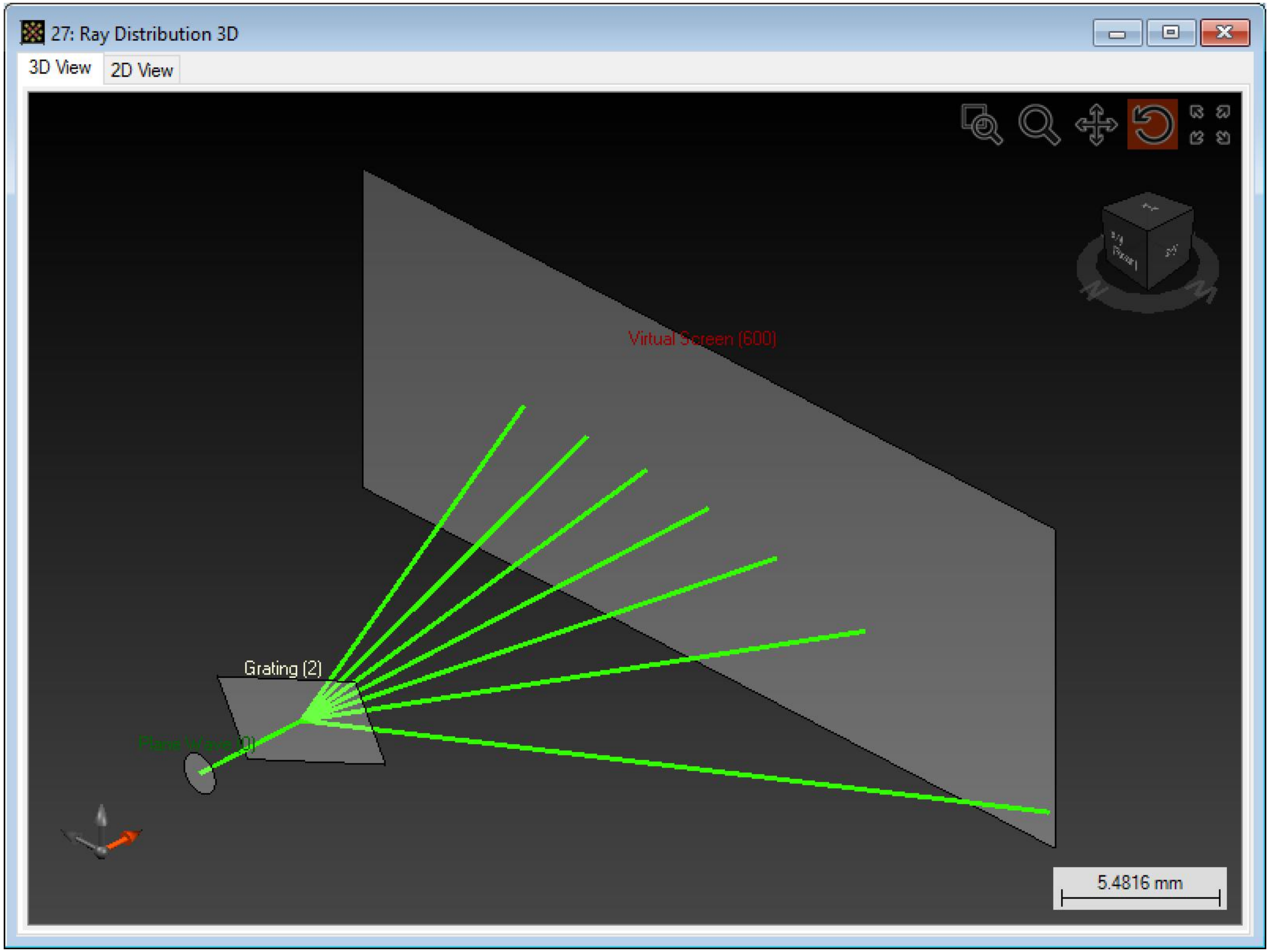
# Discrete Orders Generated by a Grating



# Grating Orders

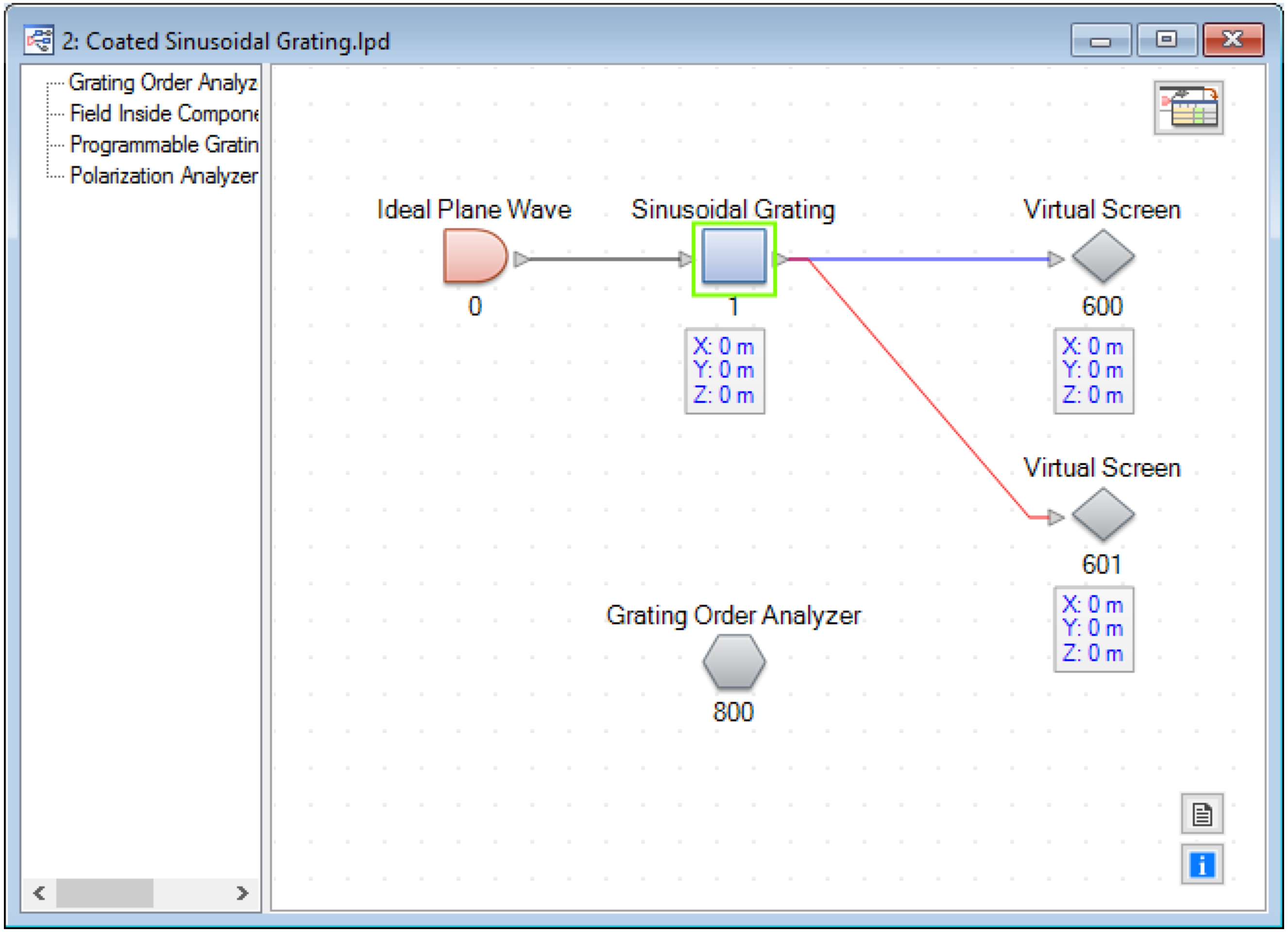
- When a grating is illuminated with a laser beam, it generates a set of discrete orders depending on the period.
- The deflection of the grating orders is defined by the two-dimensional grating equation.
- The grating structure as well as the incident light determine the efficiencies of the orders.
- The efficiencies can be calculated by the Fourier modal method available in VirtualLab.
- If a linear grating is illuminated under an angle (conical incidence) the scattered orders of the grating are in general not distributed on a straight line.
- This is also included in the simulation of grating systems in VirtualLab.

# Conical Incidence on a Grating



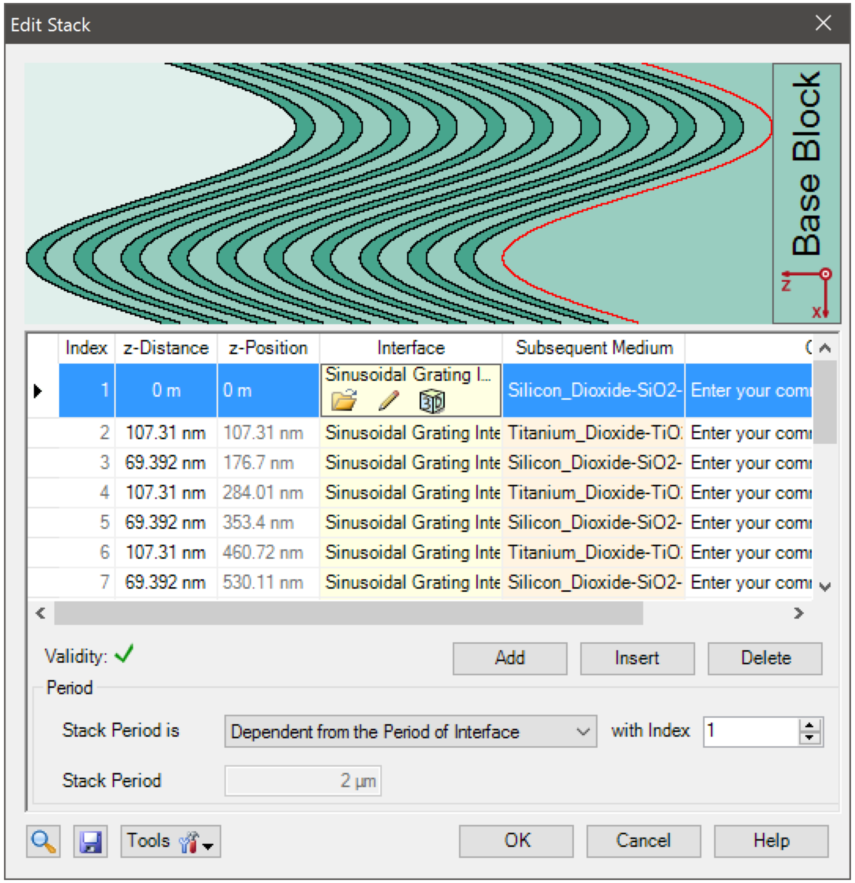
## Applied VirtualLab Techniques and Tools

# Sample File




Filename: Coated Sinusoidal Grating.lpd

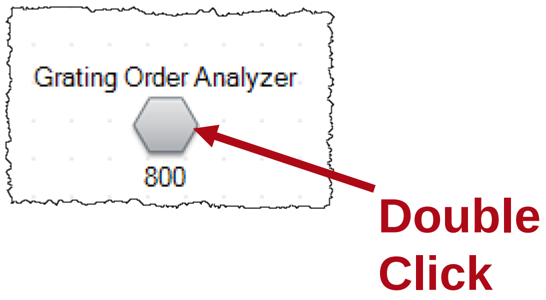
# Grating Specification




- For the demonstration of the Grating Order Analyzer for 1D gratings we use a coated sinusoidal grating.
- The grating parameters can be specified within the stack that can be accessed in the edit dialog of the grating component.

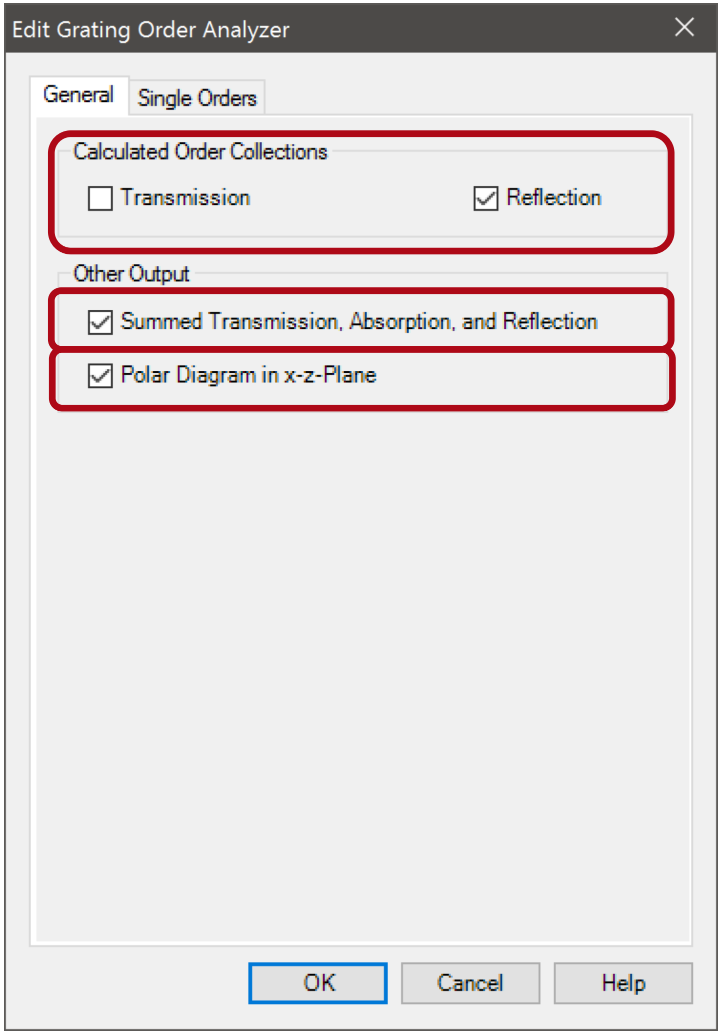
# Grating Order Analyzer

- After the grating structure has been defined you can configure the grating order analyzer.
- Various output options can be specified.
- This is done through the edit dialog of the analyzer which is opened by double clicking on the light path element in the light path view.



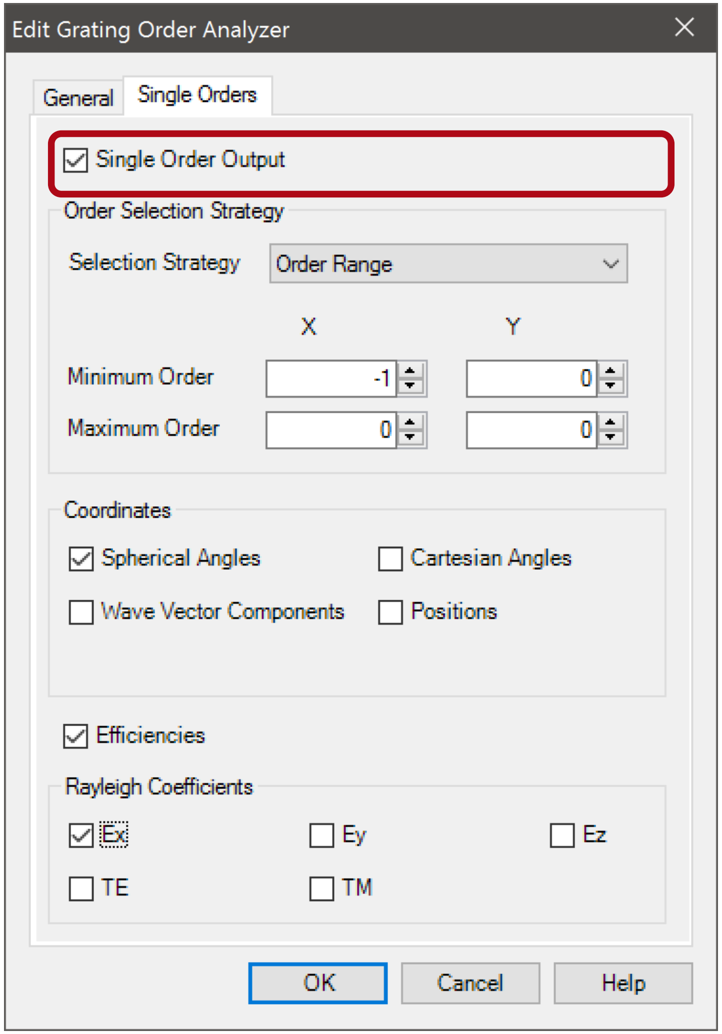

- The options of the analyzer will be explained in the following slides.

# Grating Order Analyzer




- In the *General* tab page you can select whether transmission and/or reflection shall be analyzed.
- In addition you can specify whether you would like to evaluate the summed transmission, absorbtion and reflection values and whether you would like to show a polar diagram.

# Grating Order Analyzer

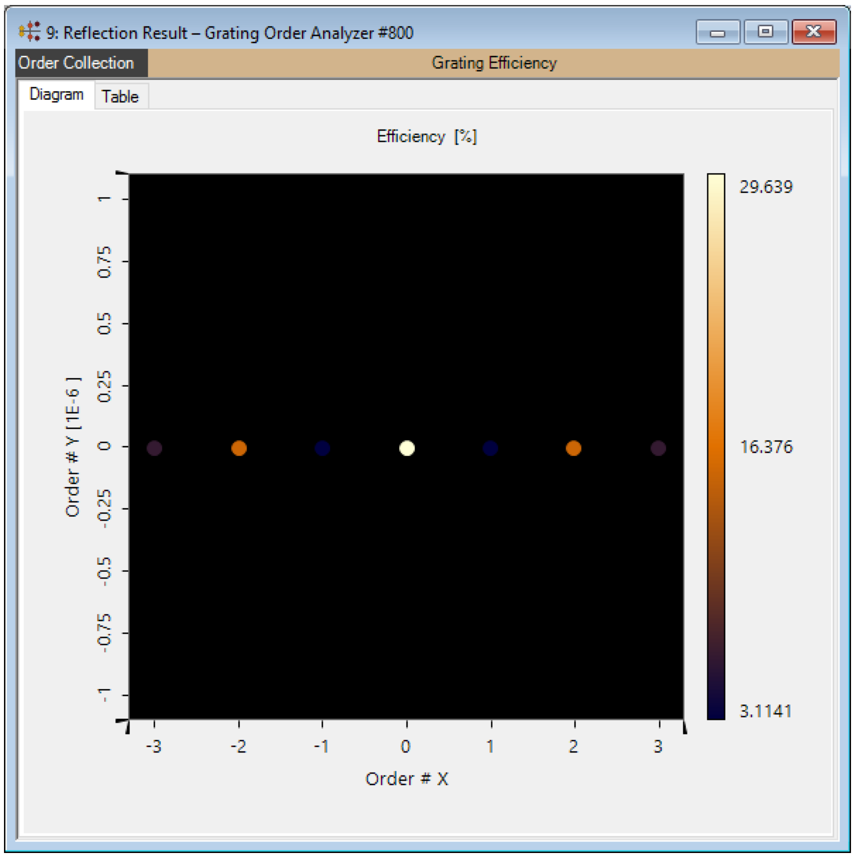



- In the *Single Orders* tab you can select whether information for single orders shall be logged.
- This option is very helpful if you would like to use the parameter run or the parametric optimization of VirtualLab to analyze and optimize specific orders of a grating.

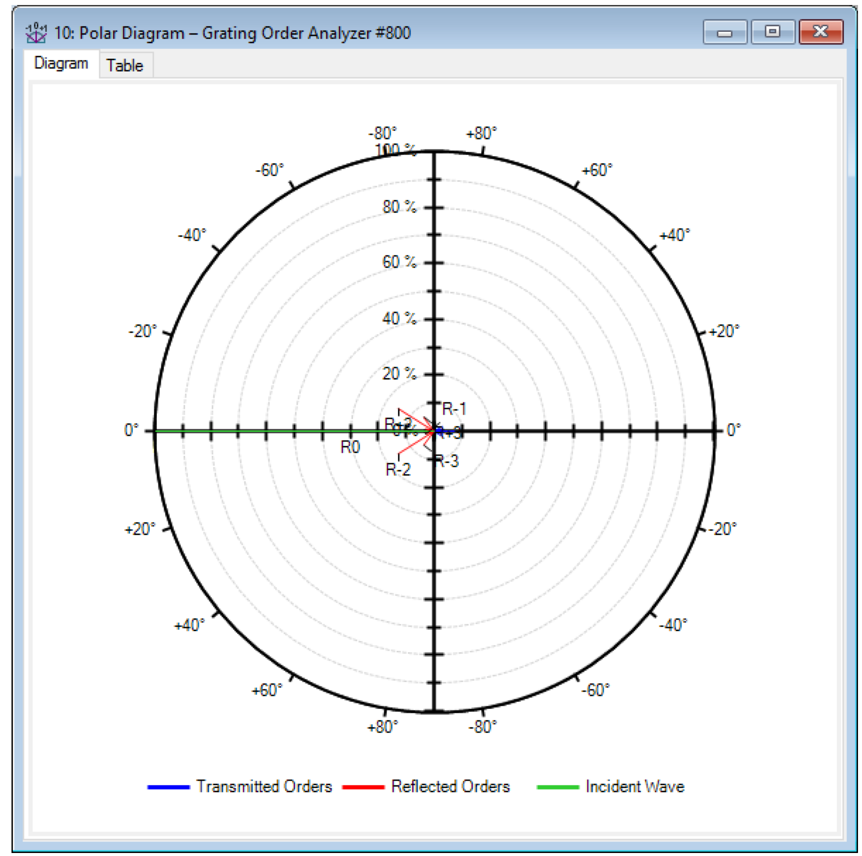
# Options for Single Order Output

| Parameter | Description |
|---|---|
| Order Selection Strategy | The user can define which order shall be evaluated. The user can define whether to analyze **All** orders, analyze only those orders which have an efficiency **Above a Given Threshold** or calculate only orders in a manually defined **Order Range**. Depending on the selection strategy the user has to define additional parameters. |
| Coordinates | Logging of the coordinates of the orders is also supported. The user can specify whether to show the coordinates in **Spherical Angles**, **Cartesian Angles**, **Wave Vector Components** or **Positions**. For the Position calculation a z-distance between the grating and the screen has to be specified. |
| Efficiencies | The user can select whether efficiencies shall be logged. |
| Rayleigh Coefficients | In addition it is possible to log the Rayleigh coefficients. The user can select to show the coeffient $\mathbf{E_x}$, $\mathbf{E_y}$, $\mathbf{E_z}$, **TE** or **TM**. |

# Grating Order Analyzer – Outputs




Grating Order Collection




Polar Diagram

# Grating Order Analyzer – Outputs

Detector Results

| | Date/Time | Detector | Sub - Detector | Result |
|---|---|---|---|---|
| 14 | 02/02/2016 09:35:15 | Grating Order Analyzer #800 (Results for Individual Orders) | Spherical Angle Theta R[-1; 0] | 15.422° |
| 13 | | | Spherical Angle Phi R[-1; 0] | 0° |
| 12 | | | Efficiency R[-1; 0] | 3.1141 % |
| 11 | | | Amplitude of Rayleigh coefficient Ex R[-1; 0] | 173.26 mV/m |
| 10 | | | Phase of Rayleigh coefficient Ex R[-1; 0] | 3.0575 rad |
| 9 | | | Spherical Angle Theta R[0; 0] | 0° |
| 8 | | | Spherical Angle Phi R[0; 0] | 0° |
| 7 | | | Efficiency R[0; 0] | 29.639 % |
| 6 | | | Amplitude of Rayleigh coefficient Ex R[0; 0] | 544.42 mV/m |
| 5 | | | Phase of Rayleigh coefficient Ex R[0; 0] | 1.4436 rad |
| 4 | 02/02/2016 09:35:15 | Grating Order Analyzer #800 | Overall Reflection Efficiency | 78.661 % |
| 3 | | | Overall Transmission Efficiency | 21.339 % |
| 2 | | | Overall Reflection and Transmission Efficiency | 100 % |
| 1 | | | Absorption | 0 % |

Grating Order Analyzer #800
(Results for Individual Orders)

Messages | Detector Results

- If the Grating Order analyzer is processed within the Light Path Diagram, the single order output values are logged into the detector results tab.
- These values are also available in the parameter run and the parametric optimization.

# Grating Order Output: Polar Diagram

# Polar Diagram

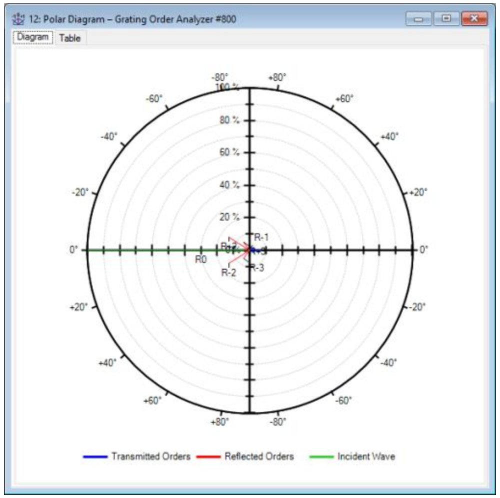


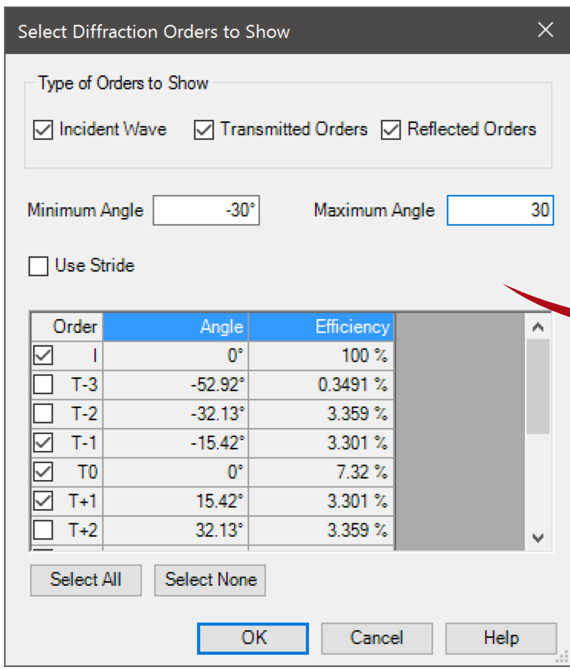

Diagram | Table

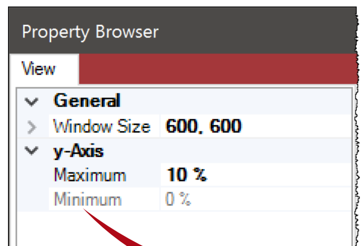
| Order | Angle | Efficiency |
|---|---|---|
| I | 0° | 100 % |
| T-3 | -52.919° | 0.34913 % |
| T-2 | -32.131° | 3.3594 % |
| T-1 | -15.422° | 3.3009 % |
| T0 | 0° | 7.3204 % |
| T+1 | 15.422° | 3.3009 % |
| T+2 | 32.131° | 3.3594 % |
| T+3 | 52.919° | 0.34913 % |
| R-3 | 52.919° | 6.2033 % |
| R-2 | 32.131° | 15.194 % |
| R-1 | 15.422° | 3.1141 % |
| R0 | 0° | 29.639 % |
| R+1 | -15.422° | 3.1141 % |
| R+2 | -32.131° | 15.194 % |
| R+3 | -52.919° | 6.2033 % |

- The polar diagram output of the Grating Order Analyzer plots the efficiencies of both the reflected and the transmitted orders versus the angles in the x-z-plane.
- It also provides a table of all angles and efficiencies of the displayed orders.

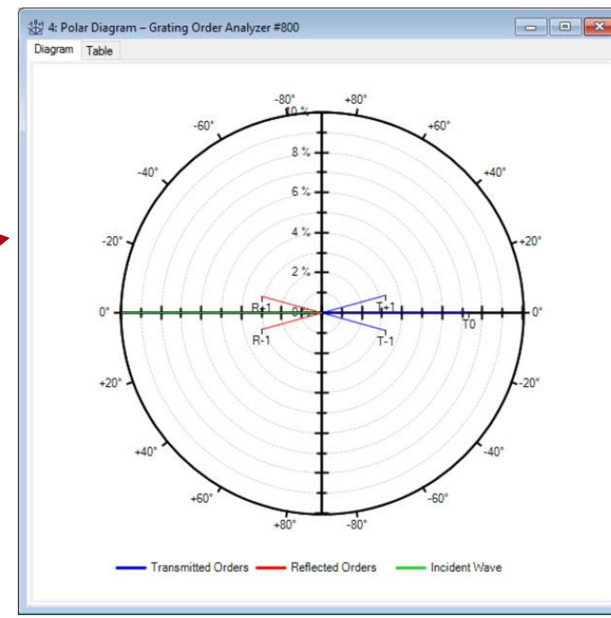
# Configuring the Polar Diagram

- You can zoom into the polar diagram with the mouse wheel, the Property Browser and the ribbon.
- You can configure which orders are shown by right-clicking on the diagram.



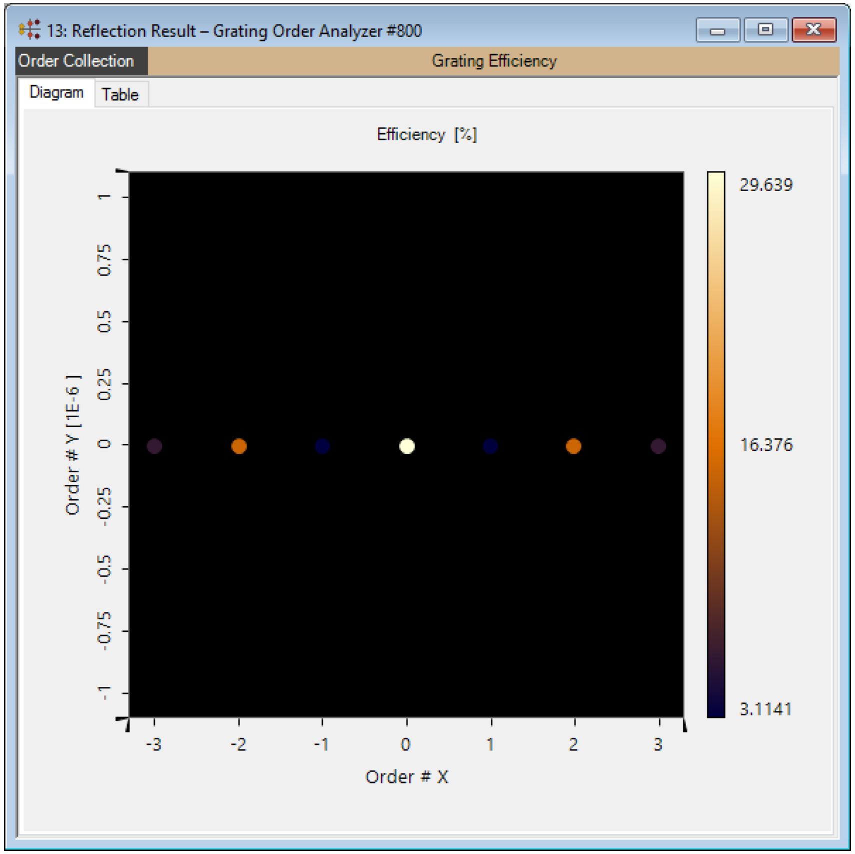




Results in



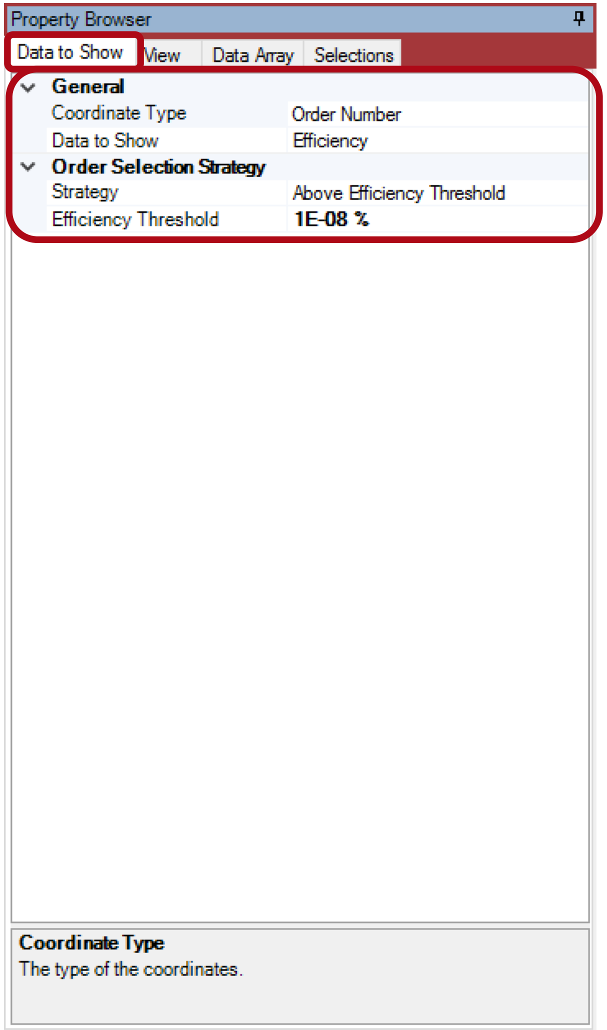
# Grating Order Output: Order Collection

# Grating Order Collection




- The Grating Order Collection object is used to visualize the calculated grating efficiencies or the Rayleigh coefficients over different coordinates.
- The user can configure the data that shall be shown by setting diverse options via the property browser.

# Setup of Data to Show

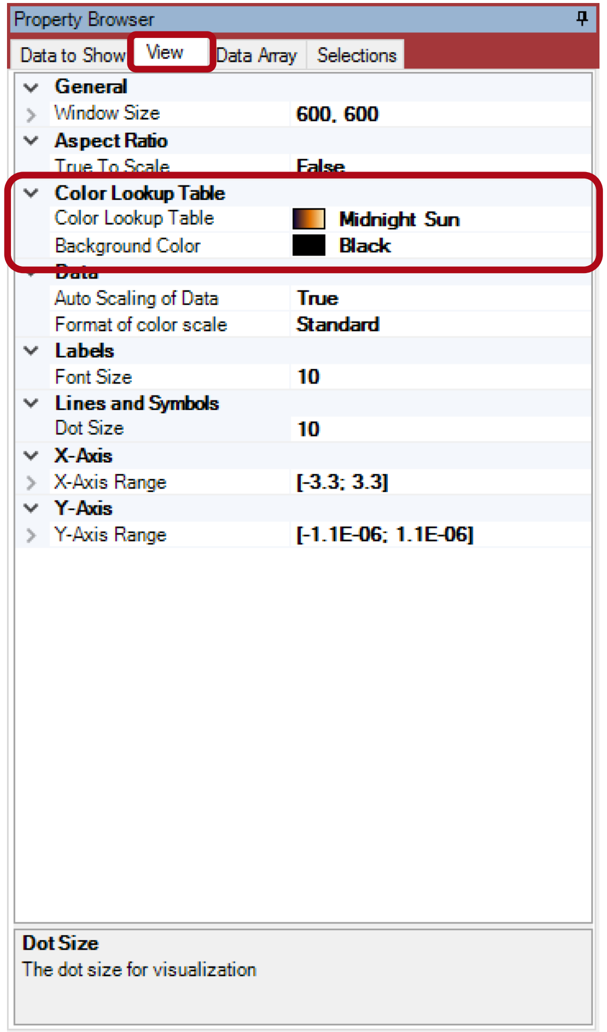



- You can specify via the property browser which data shall be shown over which coordinates.
- In addition the user can select the order to be shown in the diagram.
- These settings are done on the **Data to Show** tab page of the property browser.

# Setup of Data to Show

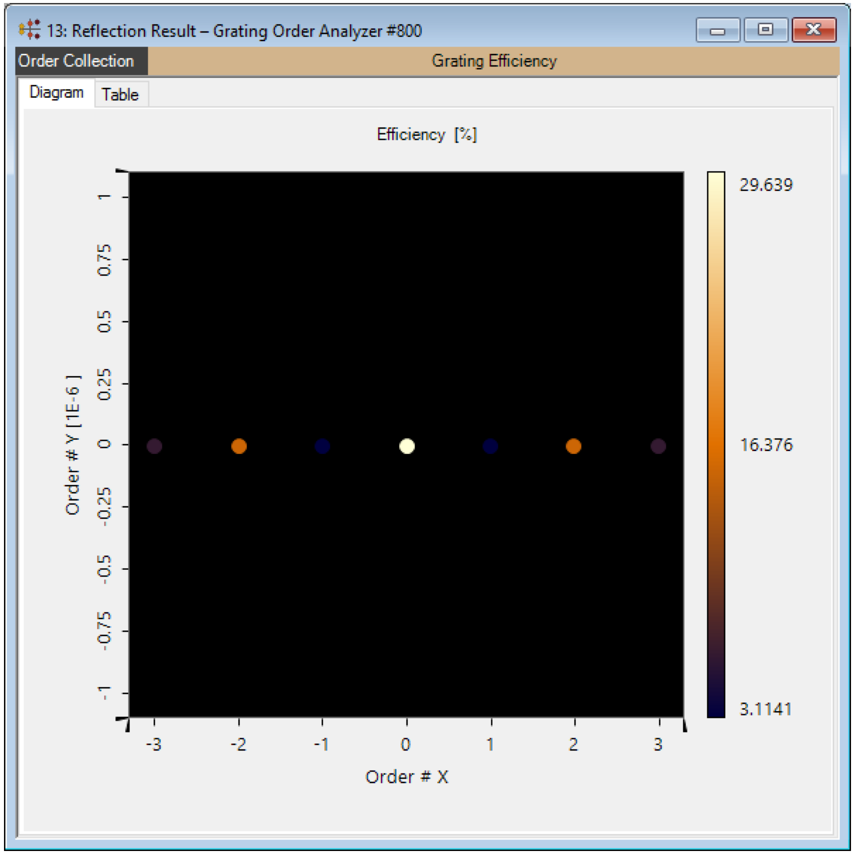
| Option | Description |
|---|---|
| Coordinate Type | This property can be used to define the coordinates over which the data shall be visualized. Currently the order collection supports the visualization over **Cartesian Angles**, **Spherical Angles**, **Wave Number Vectors** and **Positions**. |
| Data to Show | It is possible to select the different data values that should be shown. The user can select to display the efficiency or the Rayleigh coefficient over the selected coordiante type. For Rayleigh coefficents $\mathbf{E}_x$, $\mathbf{E}_y$, $\mathbf{E}_z$, **TM** and **TE** are supported. |
| Order Selection Strategy | The user can define which order shall be displayed. The user can define whether to show **All**, show only orders which have an efficiency **Above a Given Threshold** or show only orders for a manually defined **Order Range**. Depending on the selection strategy the user has to define additional parameters. |

# Setup of Additional View Settings

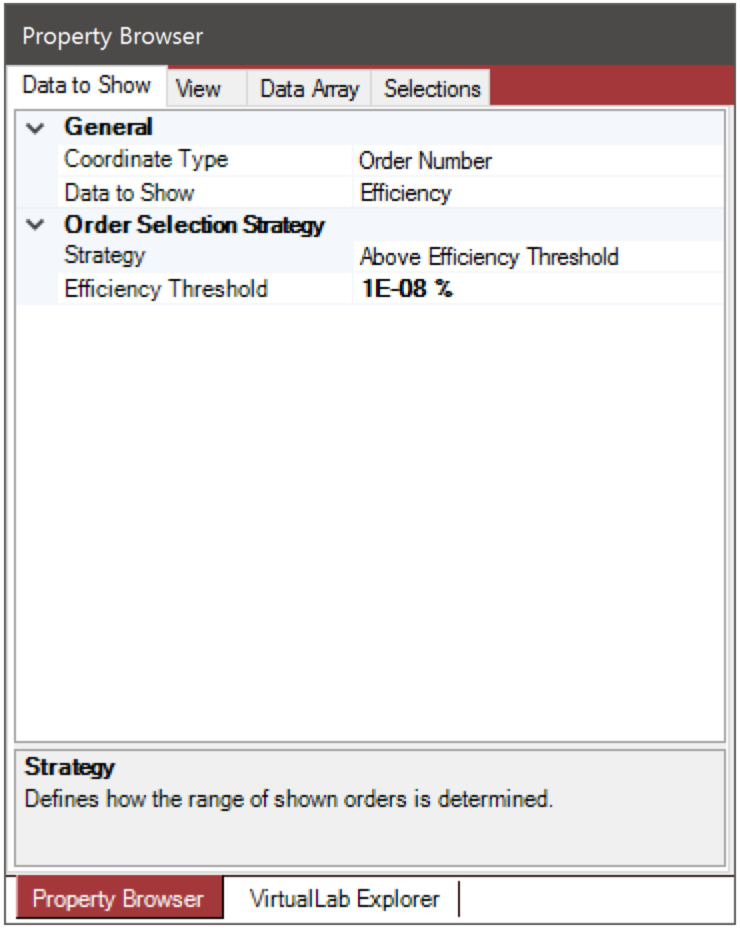



- In the **View** tab page of the property browser the user can set up additional view parameters.
- Most important for the customization of the view are the color settings.
- The user can select the background color for the view as well as the color lookup table that shall be used to define the colors for the displayed data values.

# Example of View Customization

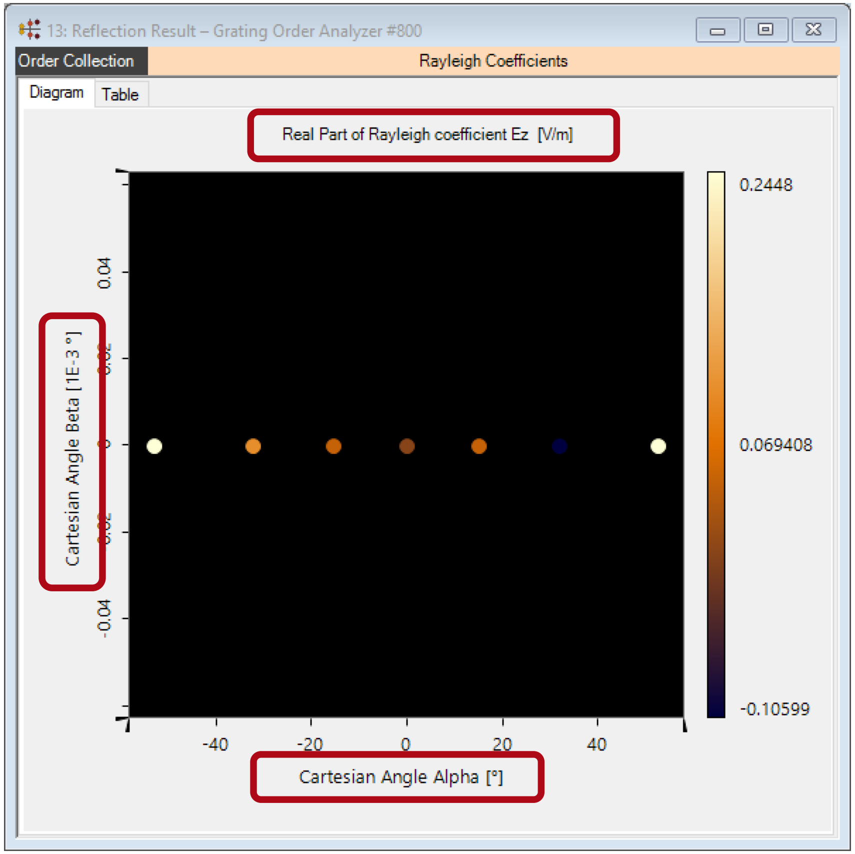



Visualization

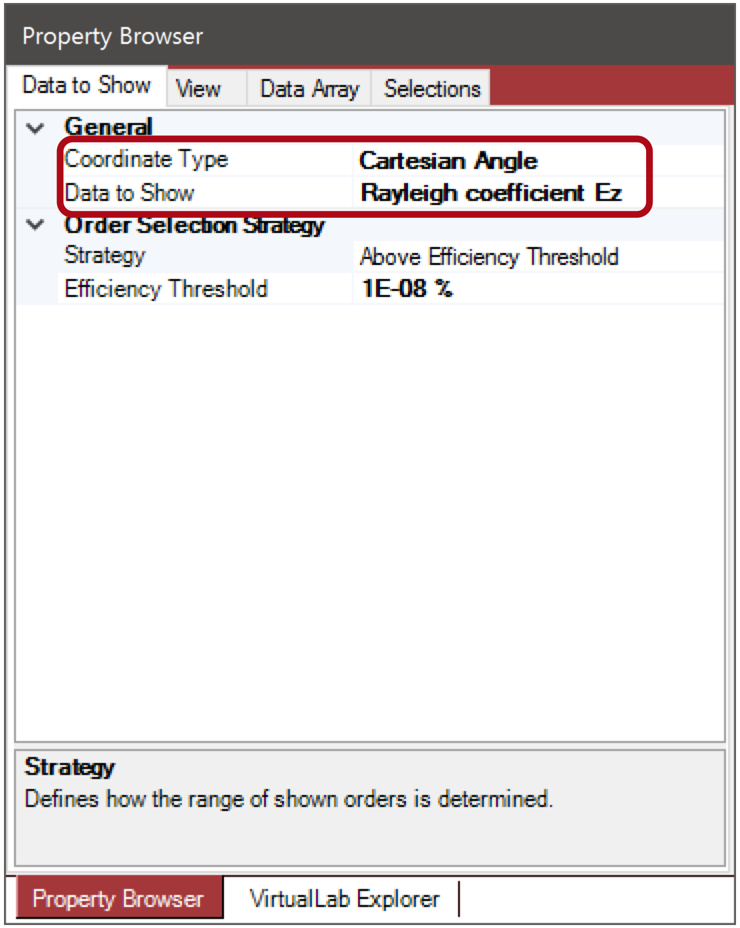



View Settings

# Example of View Customization

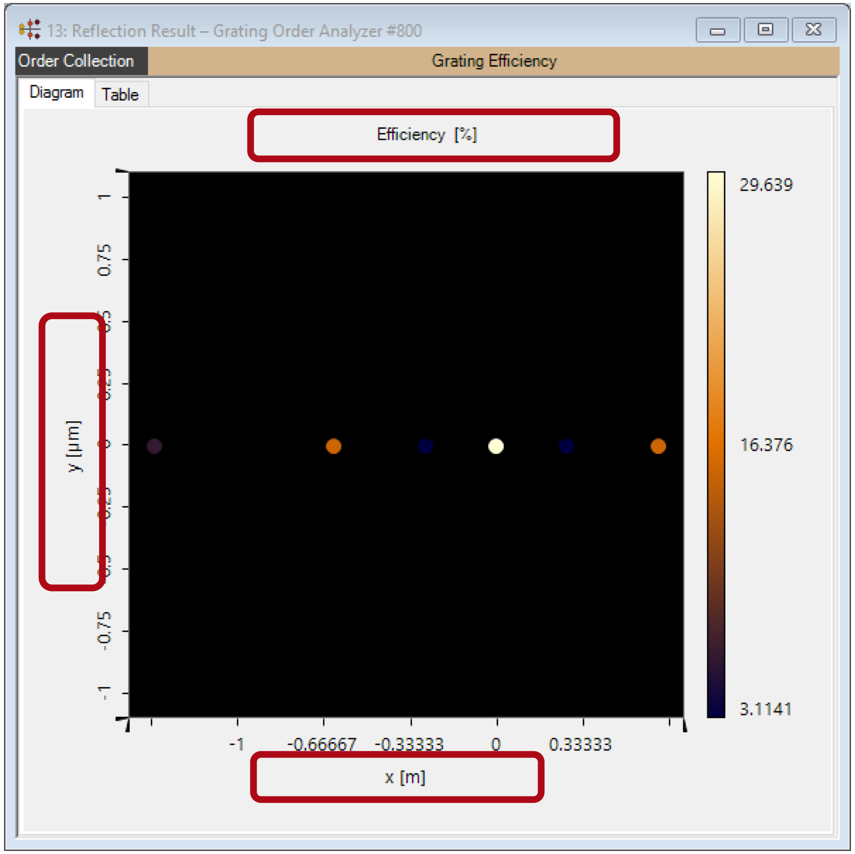



Visualization

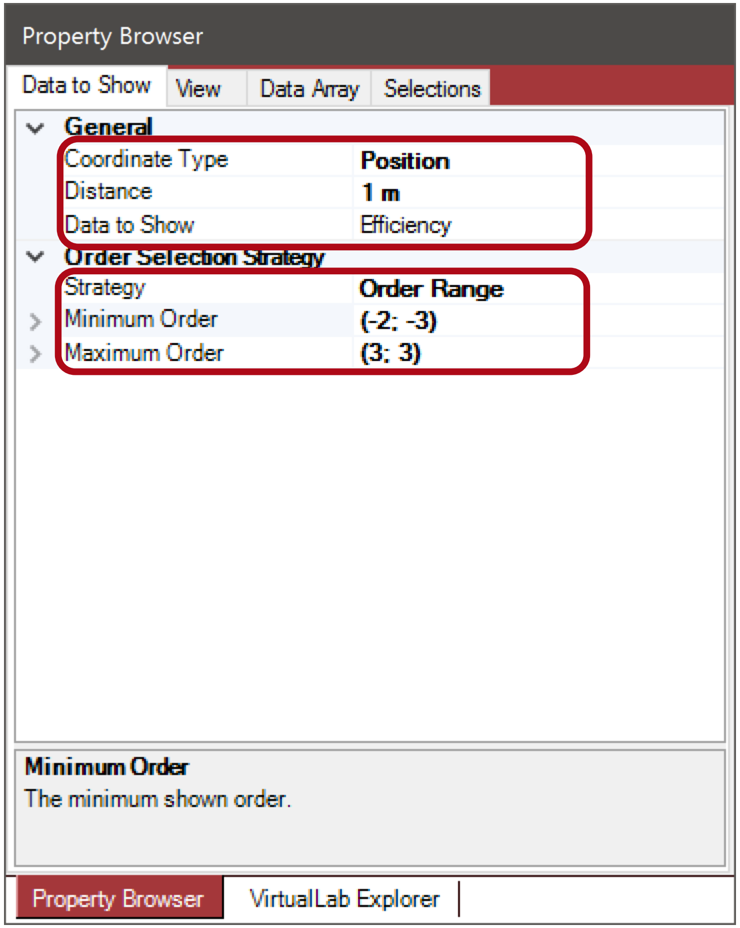



View Settings

# Example of View Customization



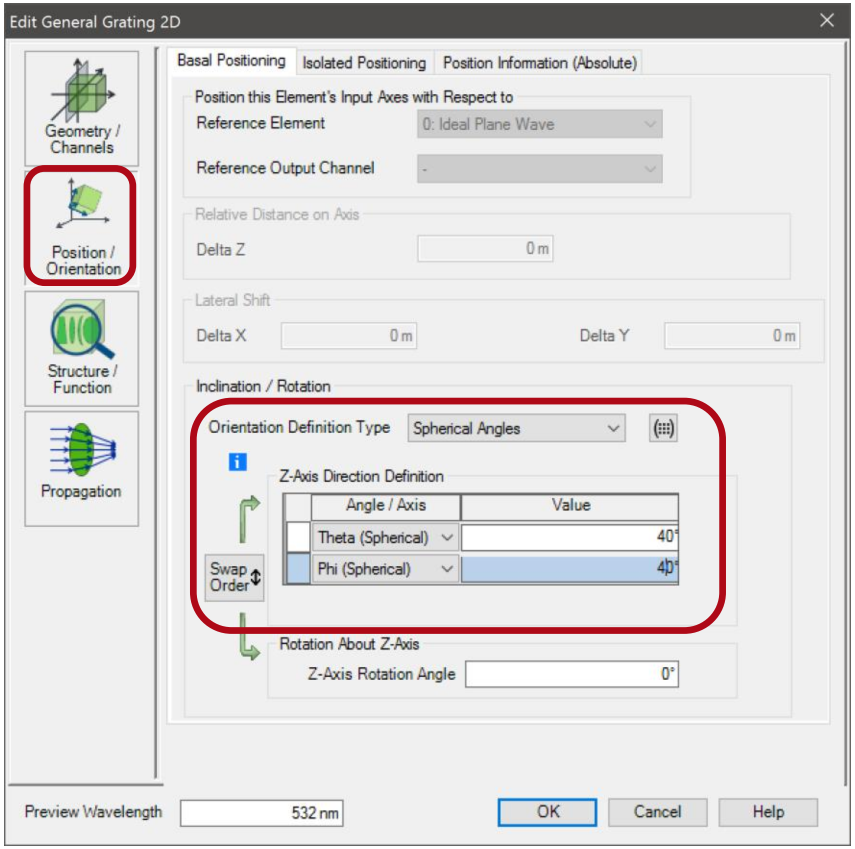

Visualization




View Settings

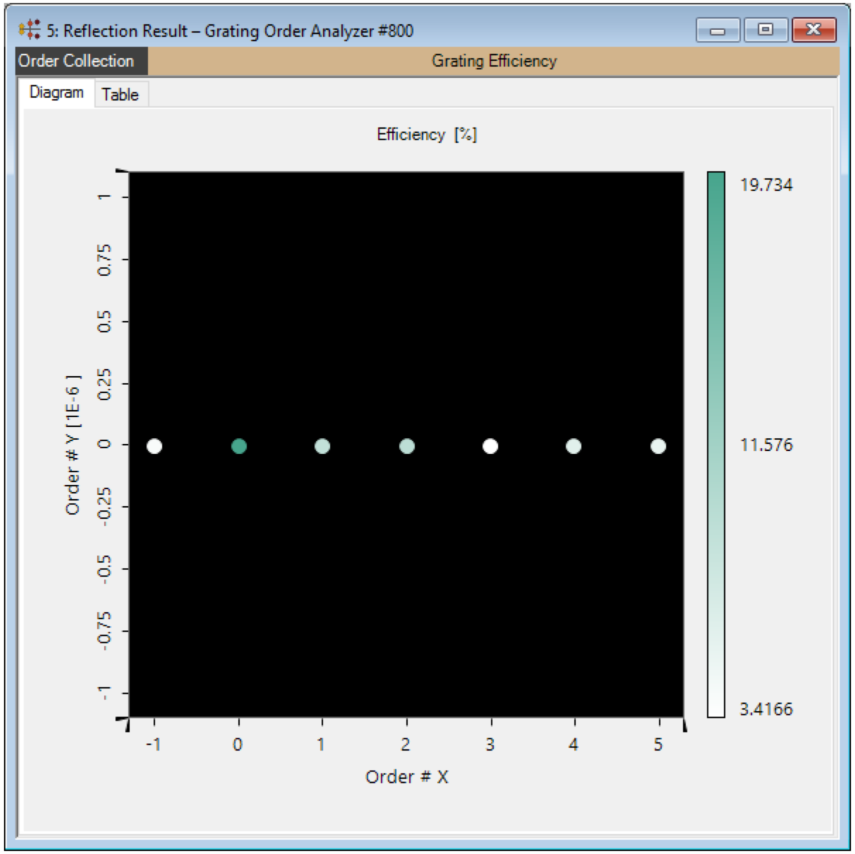
# Visualization of Conical Incidence

# Define Conical Incidence

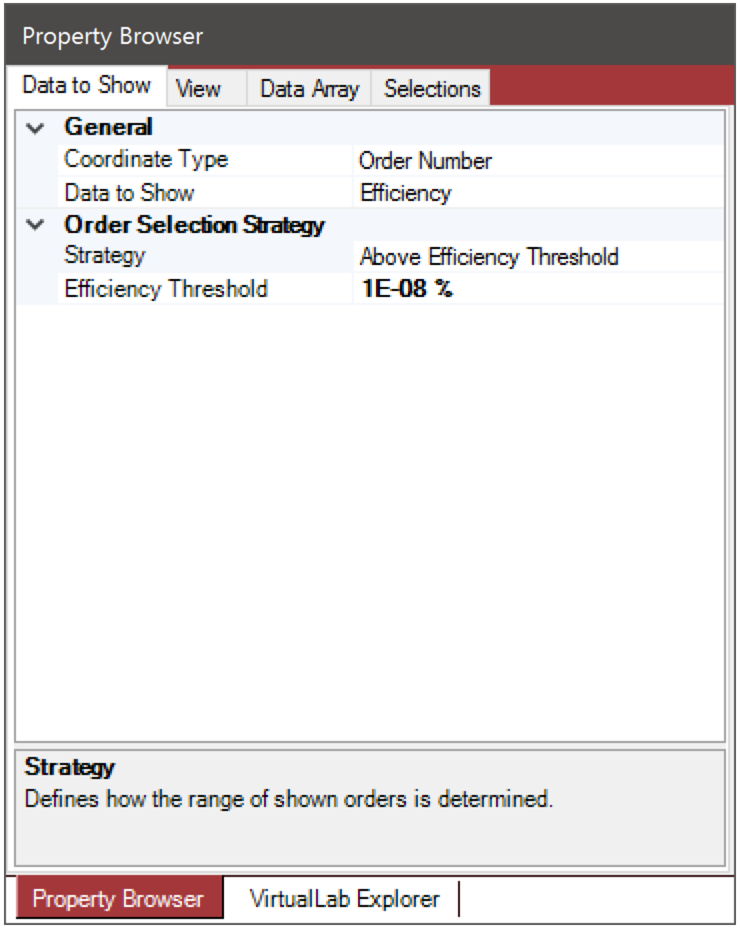



- Within the positions and orientation definition of the grating the user can define an arbitrary orientation.
- This is done in the *Position / Orientation* tab within the edit dialog of the grating.
- For this use case we use *Theta* = 40° and *Phi* = 40°.

# Result – Grating Efficiencies over Order Number

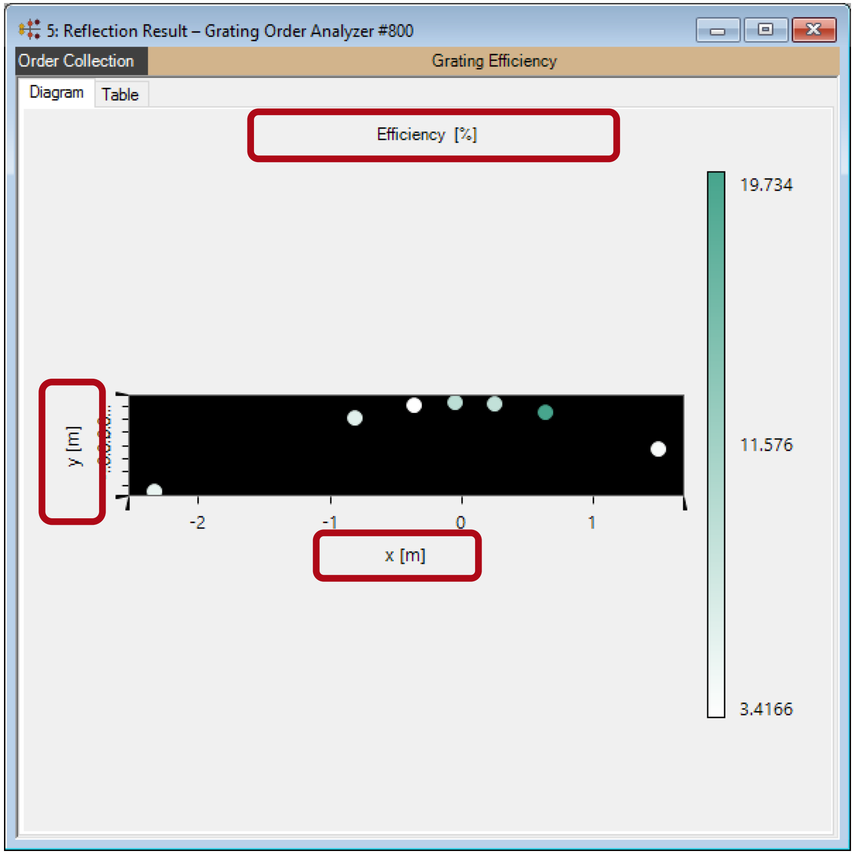



Visualization

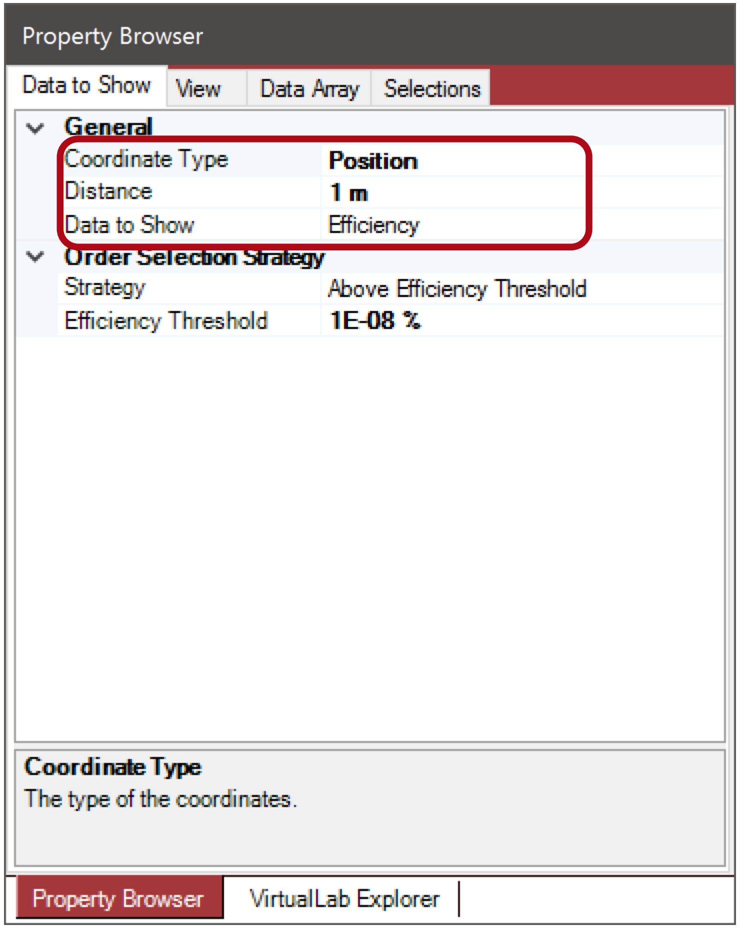



View Settings

# Result – Grating Efficiencies over Order Position

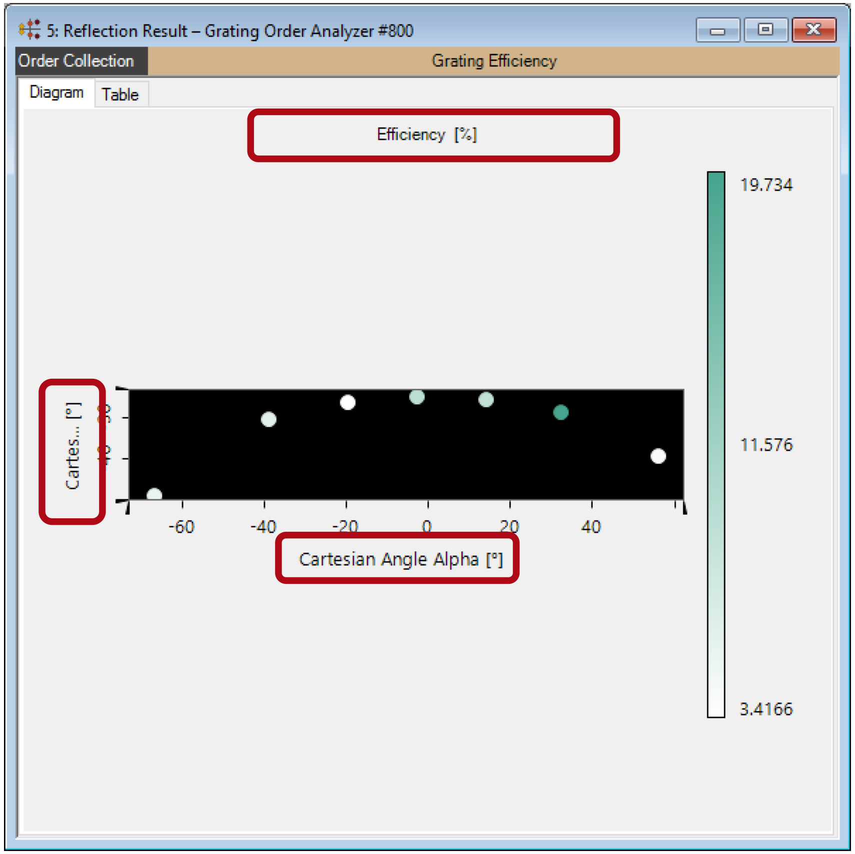



Visualization

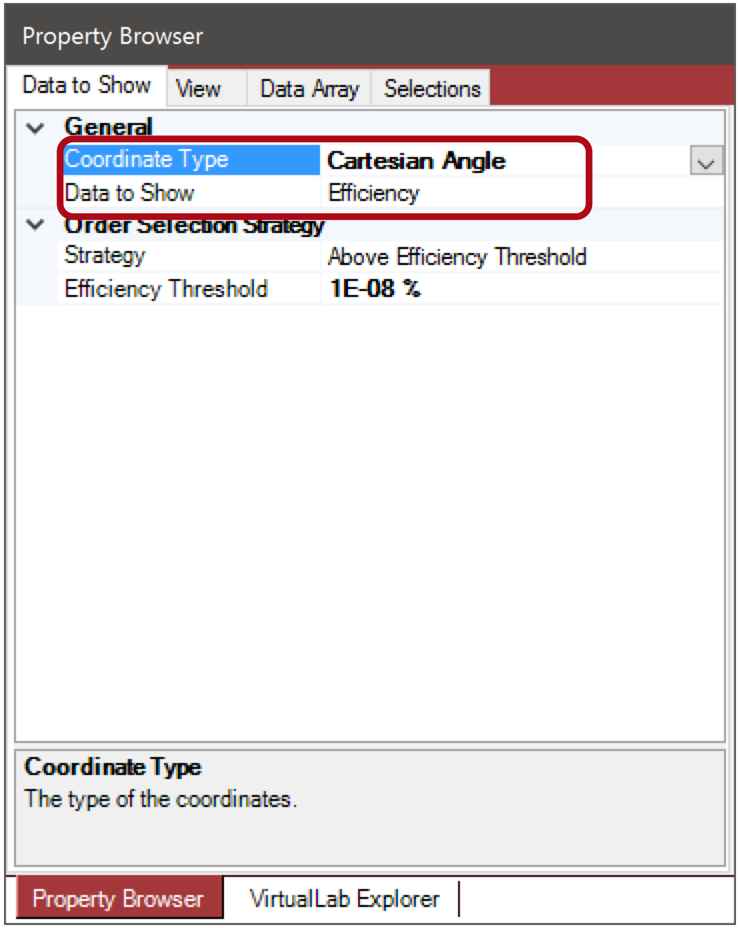



View Settings

# Result – Grating Efficiencies over Cartesian Angles

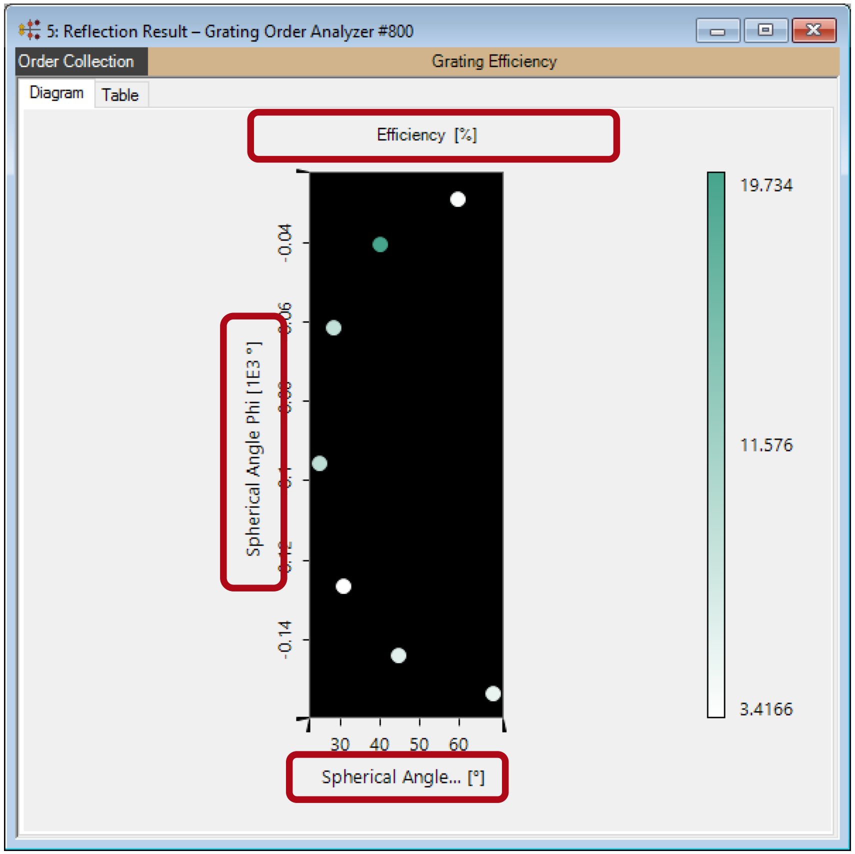



Visualization

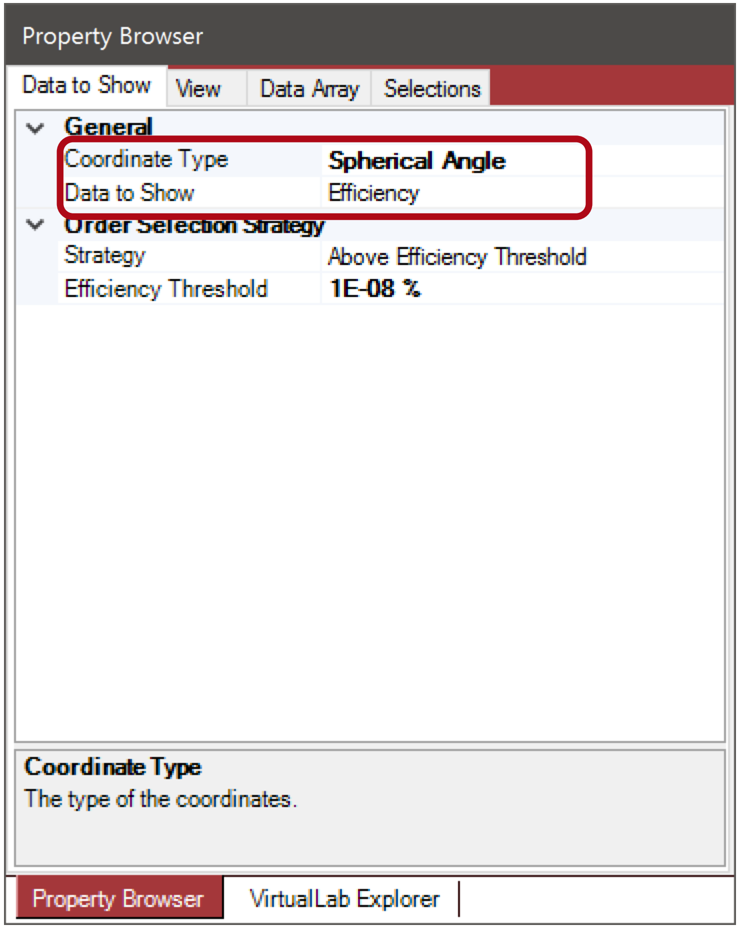



View Settings

# Result – Grating Efficiencies over Spherical Angles

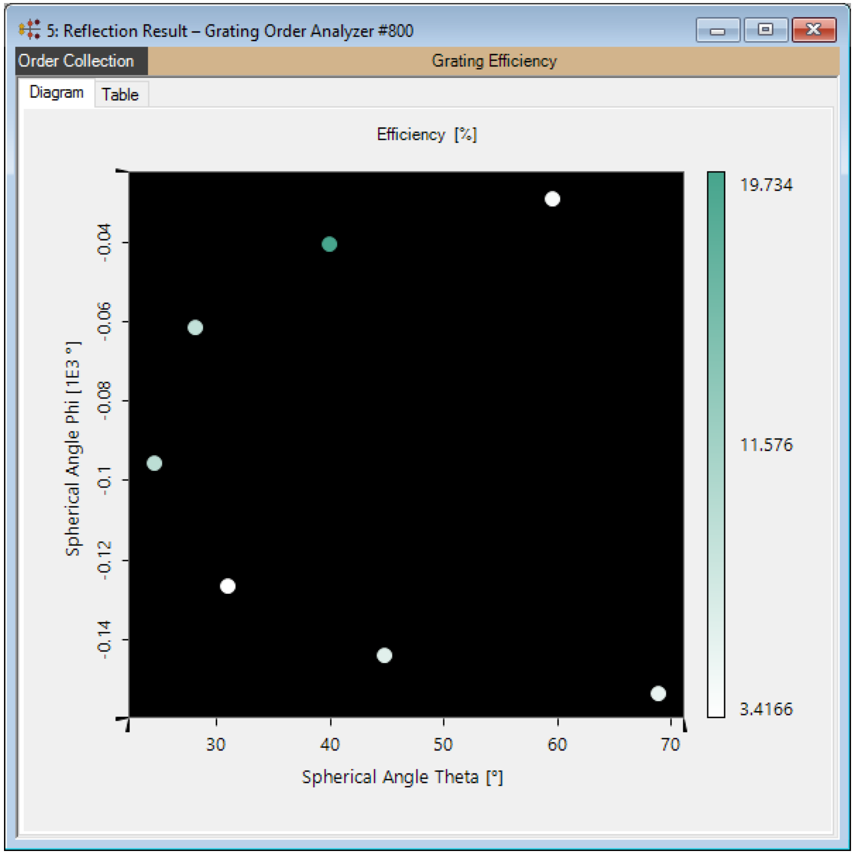



Visualization



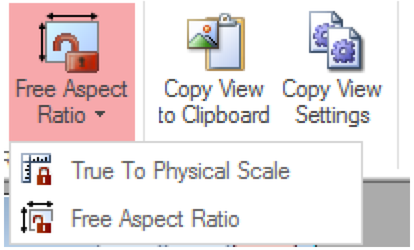

View Settings

# Tips & Tricks: Aspect Ratio




Free Aspect Ratio

- Depending on the coordinate range which is displayed it could be helpful to change the aspect ratio of the data.
- The aspect ratio can be adapted via the property browser or via the corresponding ribbon entry:

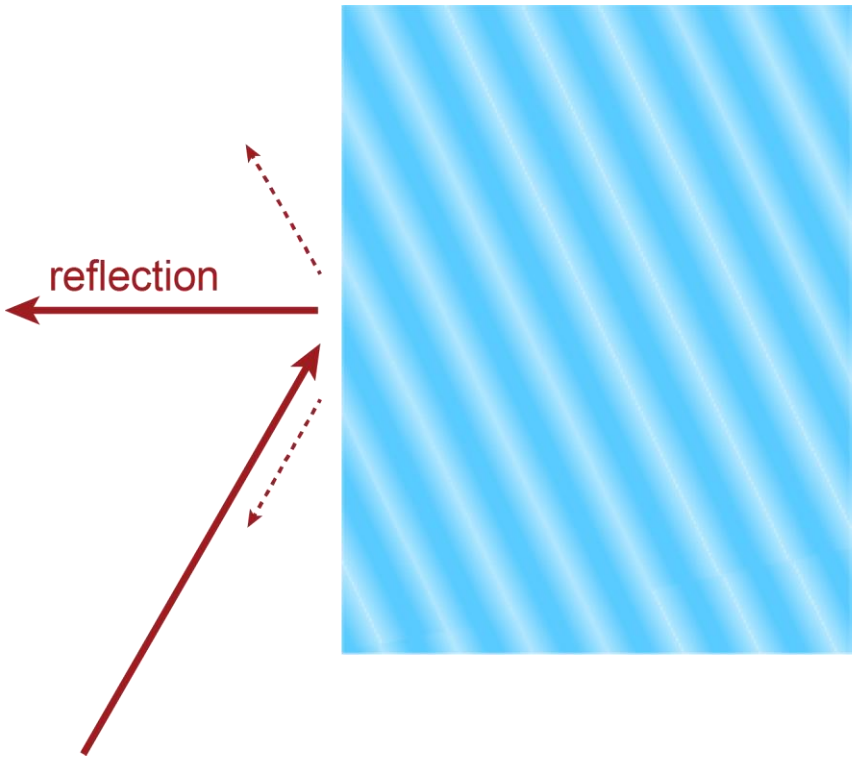


# Document Information

| | |
|---|---|
| title | Grating Order Analyzer |
| version | 1.0 |
| VL version used for simulations | 7.0.3.4 |
| category | Feature Use Case |

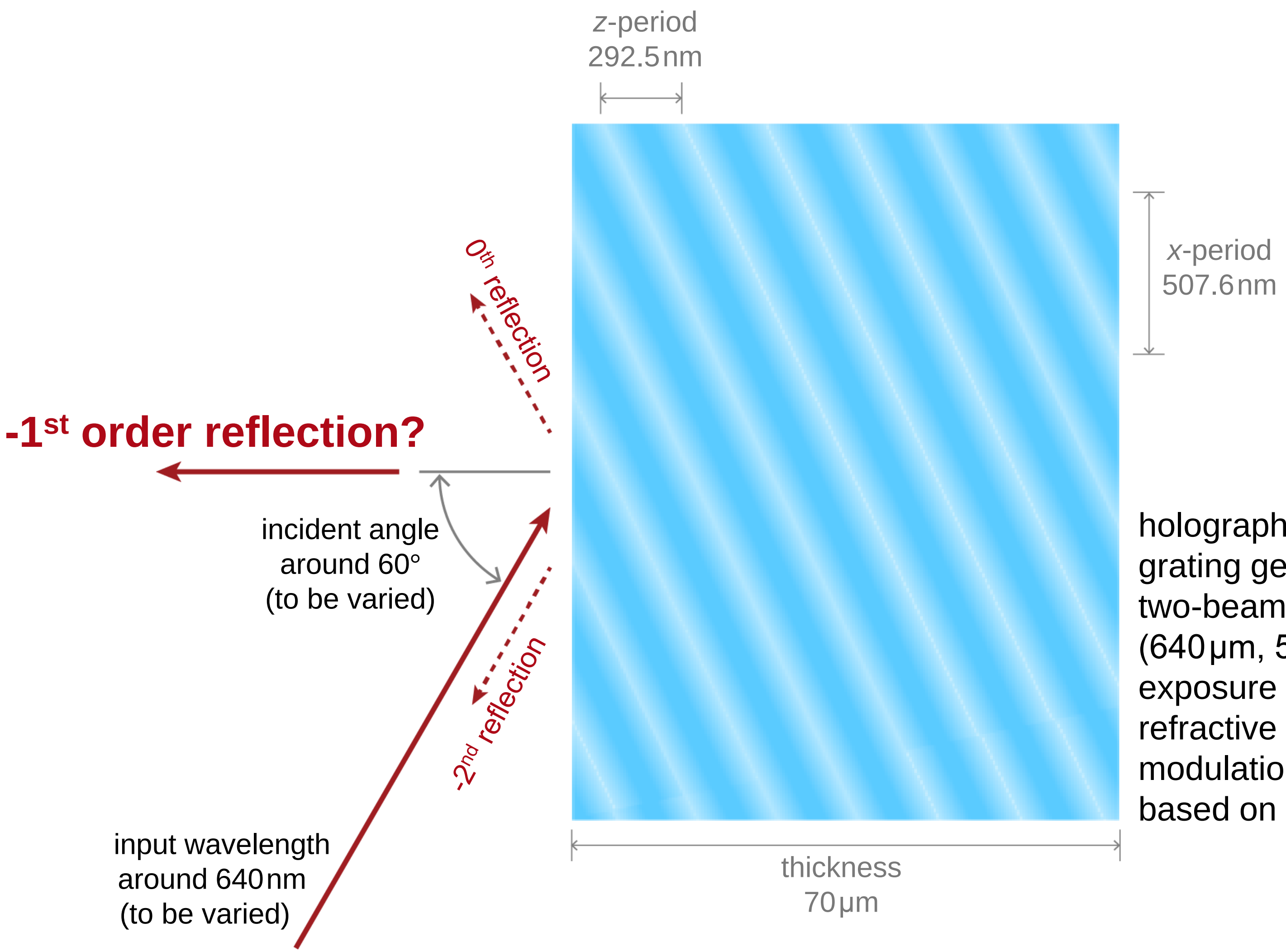
# Rigorous Simulation of Holographic Generated Volume Grating

# Abstract




Holographic generated volume gratings, with a thickness much larger than the wavelength, often shows a narrow bandwidth around particular wavelength and angle. Following the two-beam interference exposure process, a volume grating inside fused silica is generated and simulated with the rigorous Fourier modal method (FMM) in VirtualLab. Both the spectral and angular dependent reflection property of the grating are analyzed.

# Modeling Task

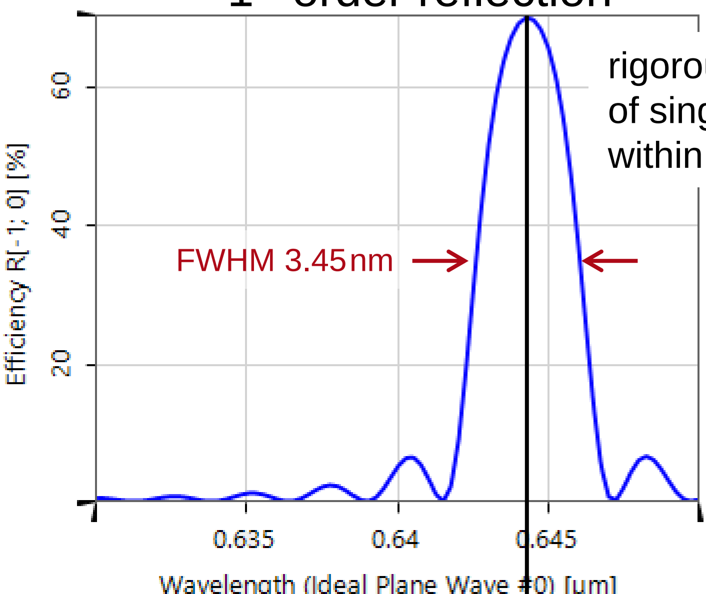



holographic volume grating generated by two-beam interference (640 µm, 59.9° angle) exposure process, with refractive index modulation of 0.01 based on fused silica

# Results

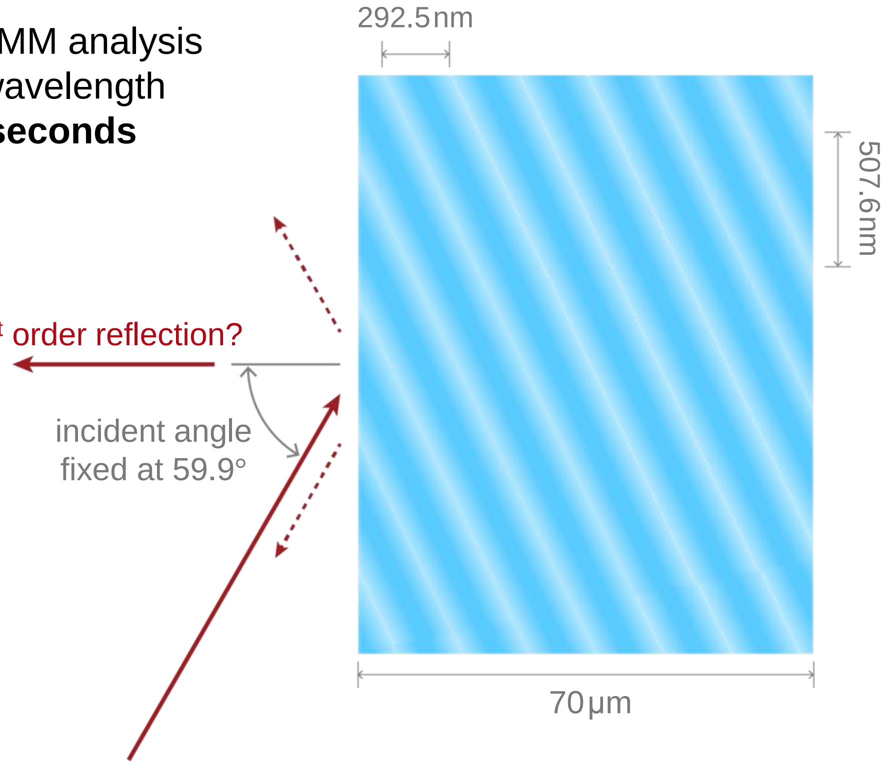
- Wavelength scanning

-1st order reflection




rigorous FMM analysis of single wavelength within **18 seconds**

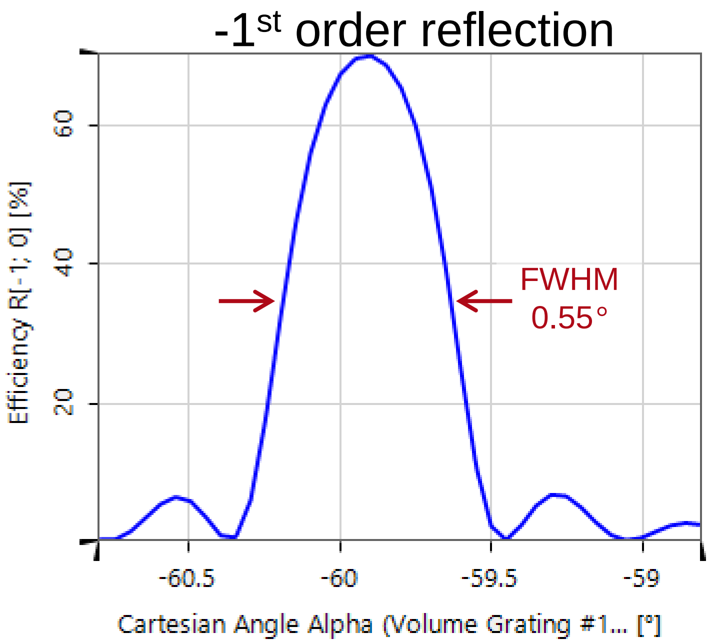
shift of wavelength dependent reflection due to locally increased effective refraction index

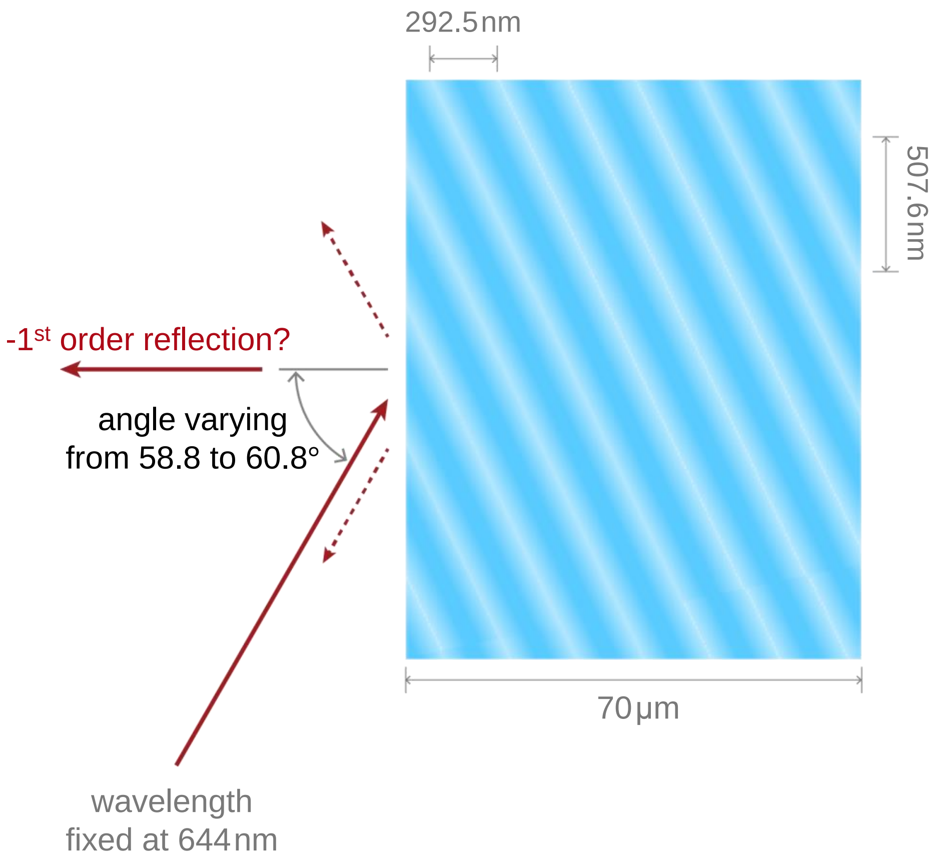



wavelength varying from 630 to 650 nm

# Results

- Angle scanning



# Document Information

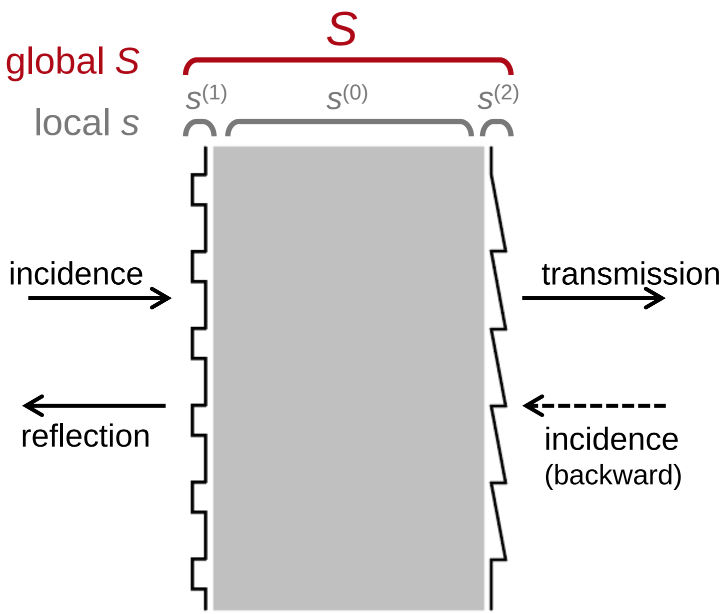
| | |
|---|---|
| title | Rigorous Simulation of Holographic Generated Volume Grating |
| version | 1.0 |
| VL version used for simulations | 7.0.3.4 |
| category | Technology Use Case |

Non-sequential Field Tracing

# Coupled Surfaces Analysis by Using Non-sequential Field Tracing

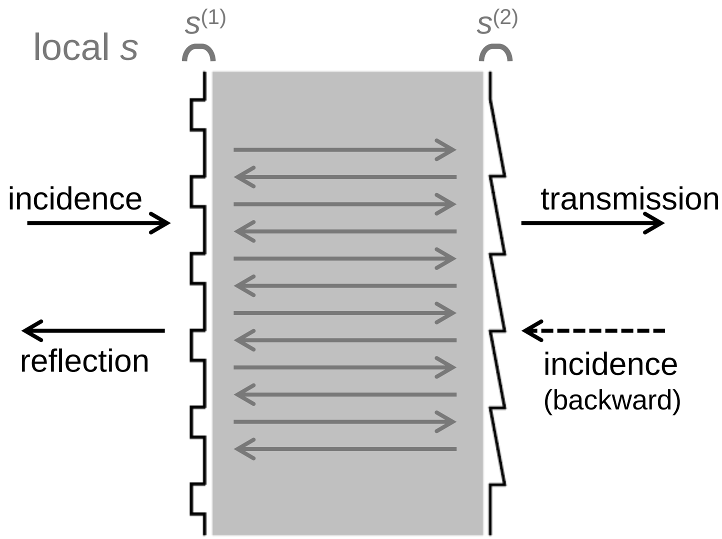
# Theory Background

- Global S matrix




  - Recursion with respect to number of regions / layers

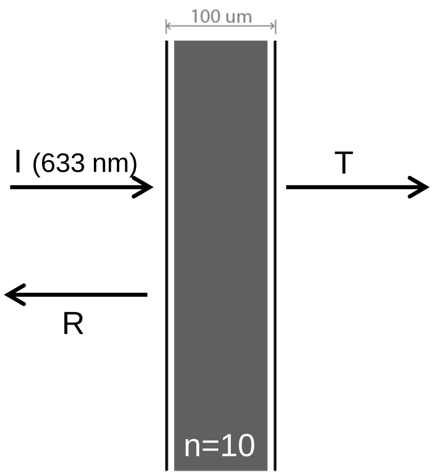
- Non-sequential field tracing




  - Recursion with respect to number of light paths

# Planar Surface + Planar Surface

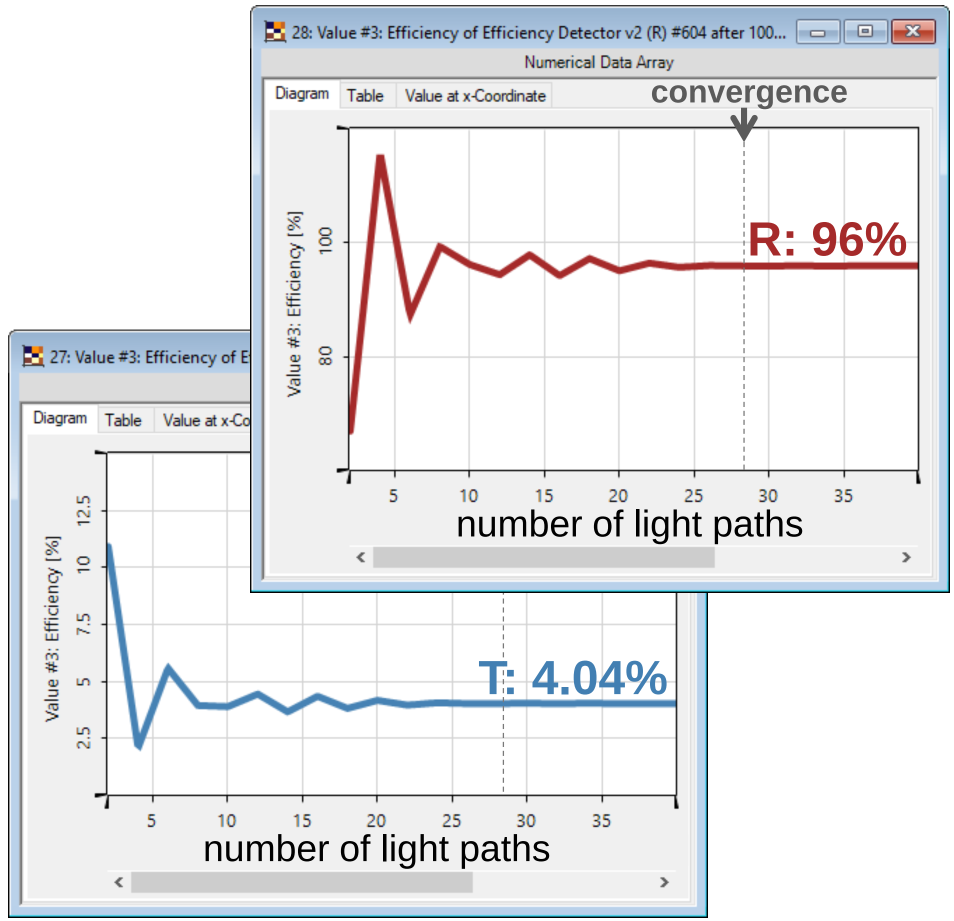
- Structure




Global S matrix

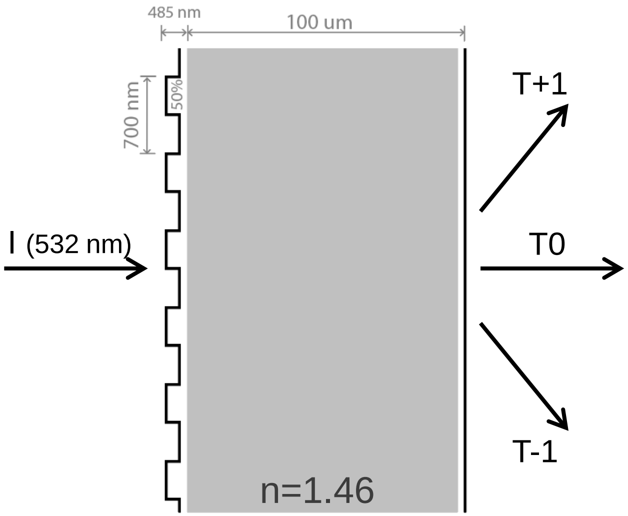
| Eff. (T) | Eff. (R) |
|---|---|
| 4.04% | 96% |

- Non-sequential field tracing



# Rectangular Grating + Backside Coating

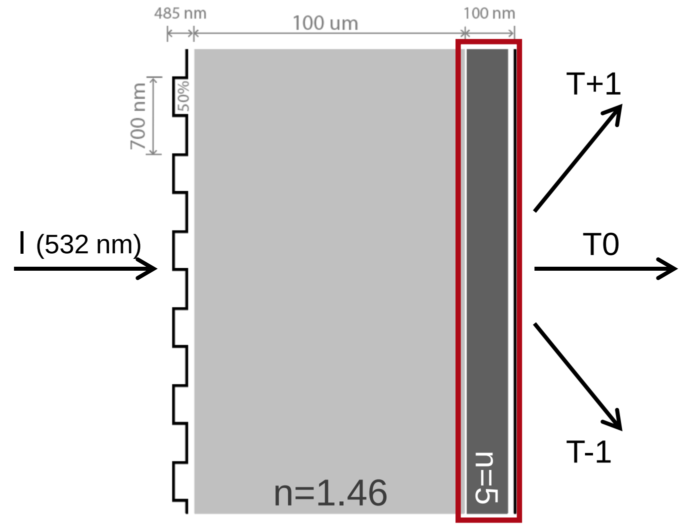
- Single grating




Global S matrix (TM)

| T | Eff. | R | Eff. |
|---|---|---|---|
| ±1 | 31.9% | ±1 | 1.26% |
| 0 | 30.6% | 0 | 3.03% |

- ... with backside coating

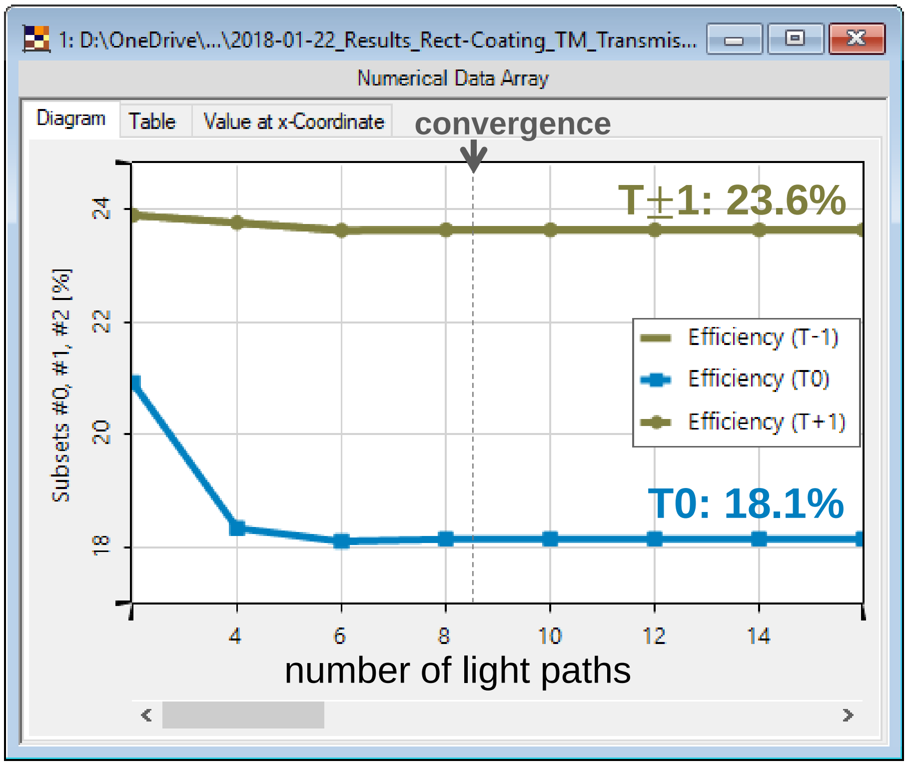



Global S matrix (TM)

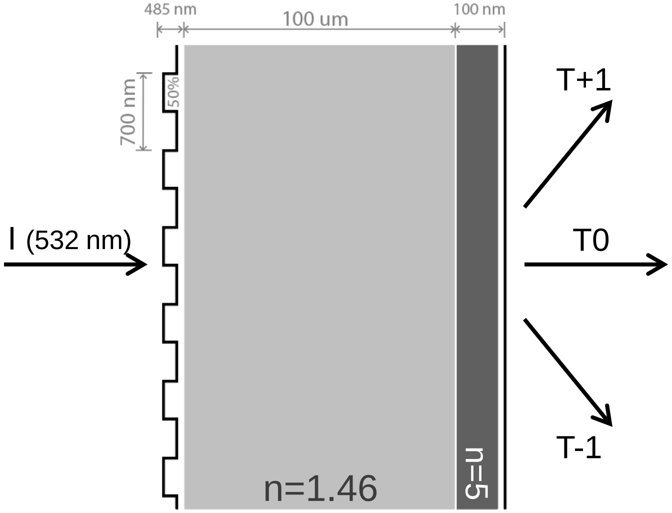
| T | Eff. | R | Eff. |
|---|---|---|---|
| ±1 | 23.6% | ±1 | 0.762% |
| 0 | 18.1% | 0 | 33.1% |

# Rectangular Grating + Backside Coating

- Non-sequential field tracing




- ... with backside coating

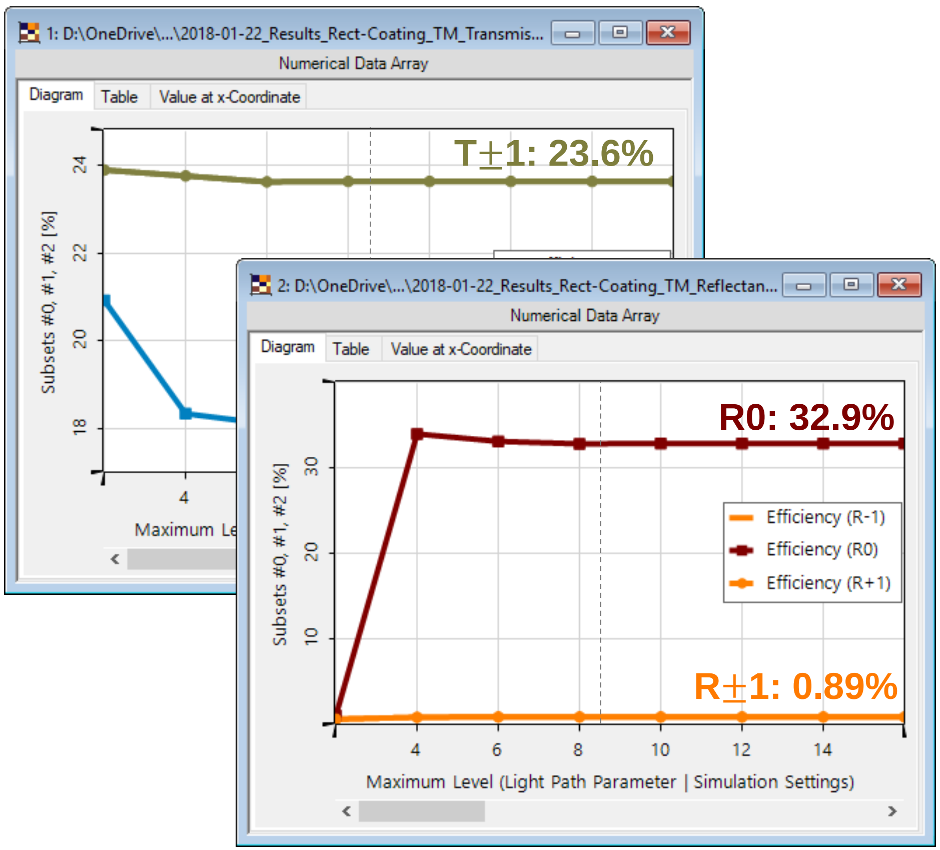



Global S matrix (TM)

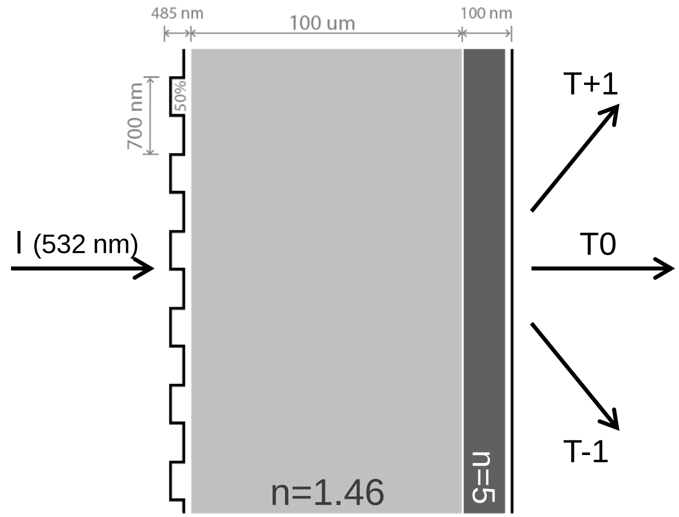
| T | Eff. | R | Eff. |
|---|---|---|---|
| ±1 | 23.6% | ±1 | 0.762% |
| 0 | 18.1% | 0 | 33.1% |

# Rectangular Grating + Backside Coating

- Non-sequential field tracing




- ... with backside coating

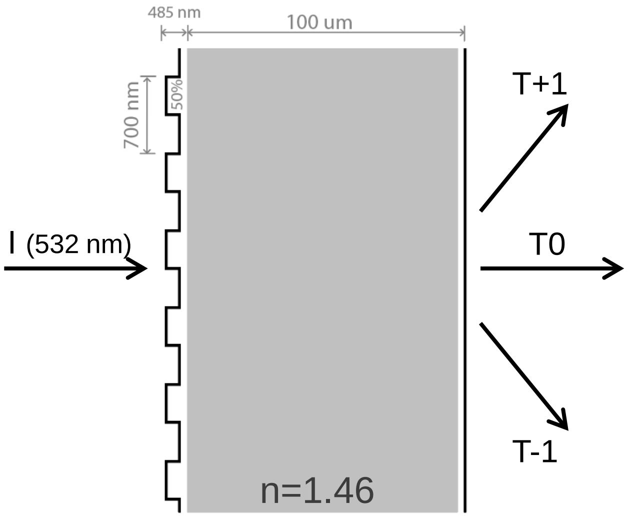



Global S matrix (TM)

| T | Eff. | R | Eff. |
|---|---|---|---|
| ±1 | 23.6% | ±1 | 0.762% |
| 0 | 18.1% | 0 | 33.1% |

# Rectangular + Sawtooth Grating (parallel)

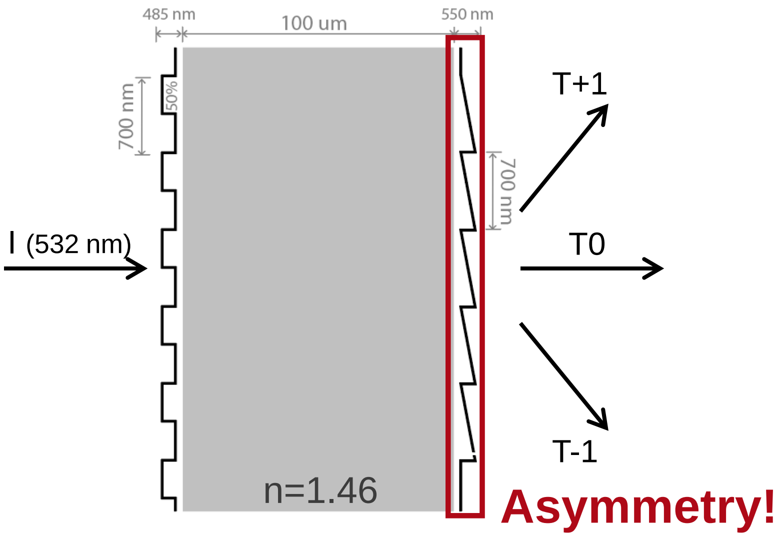
- Single grating




Global S matrix (TM)

| T | Eff. | R | Eff. |
|---|---|---|---|
| ±1 | 31.9% | ±1 | 1.26% |
| 0 | 30.6% | 0 | 3.03% |

- ... with sawtooth coating

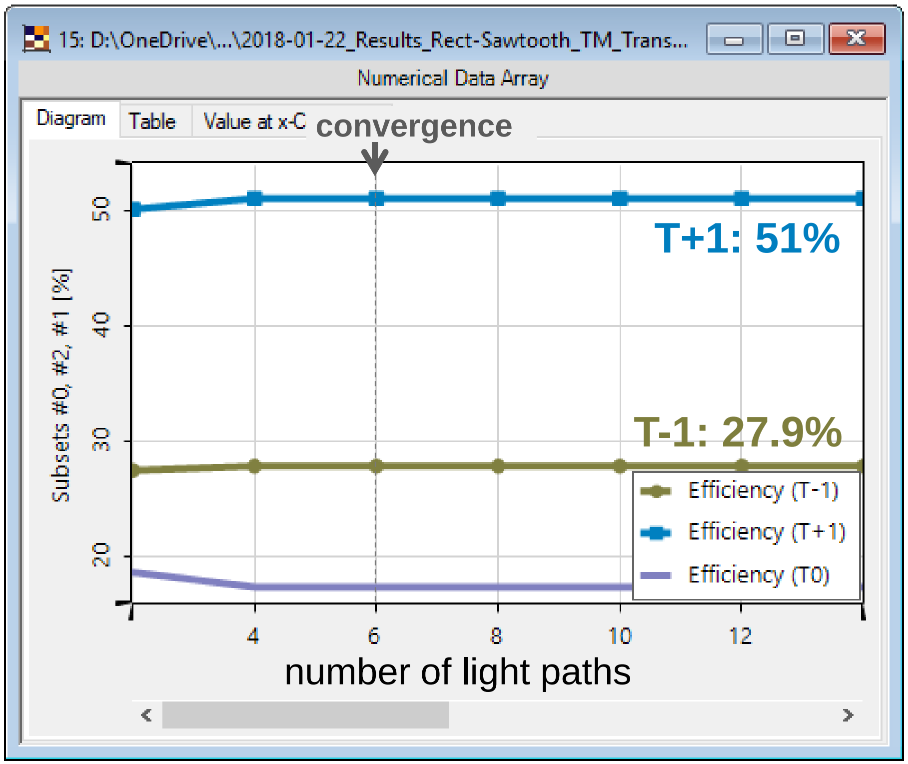



Global S matrix (TM)

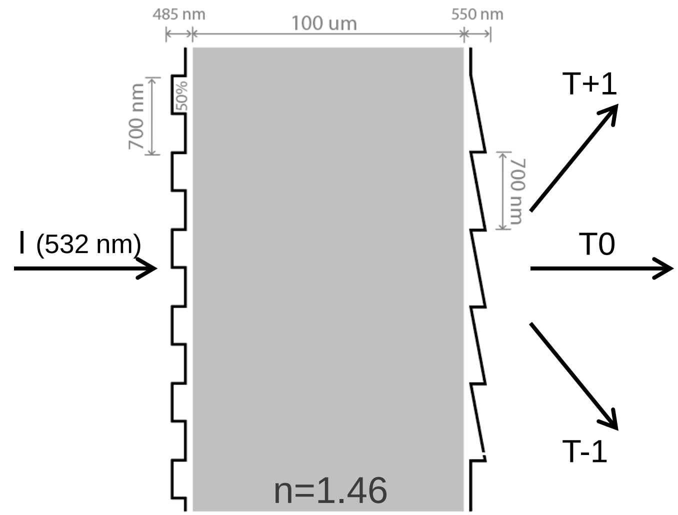
| T | Eff. | R | Eff. |
|---|---|---|---|
| -1 | 28.1% | -1 | 0.65% |
| 0 | 18.2% | 0 | 0.923% |
| +1 | 51.4% | +1 | 0.74% |

# Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing




- ... with sawtooth coating

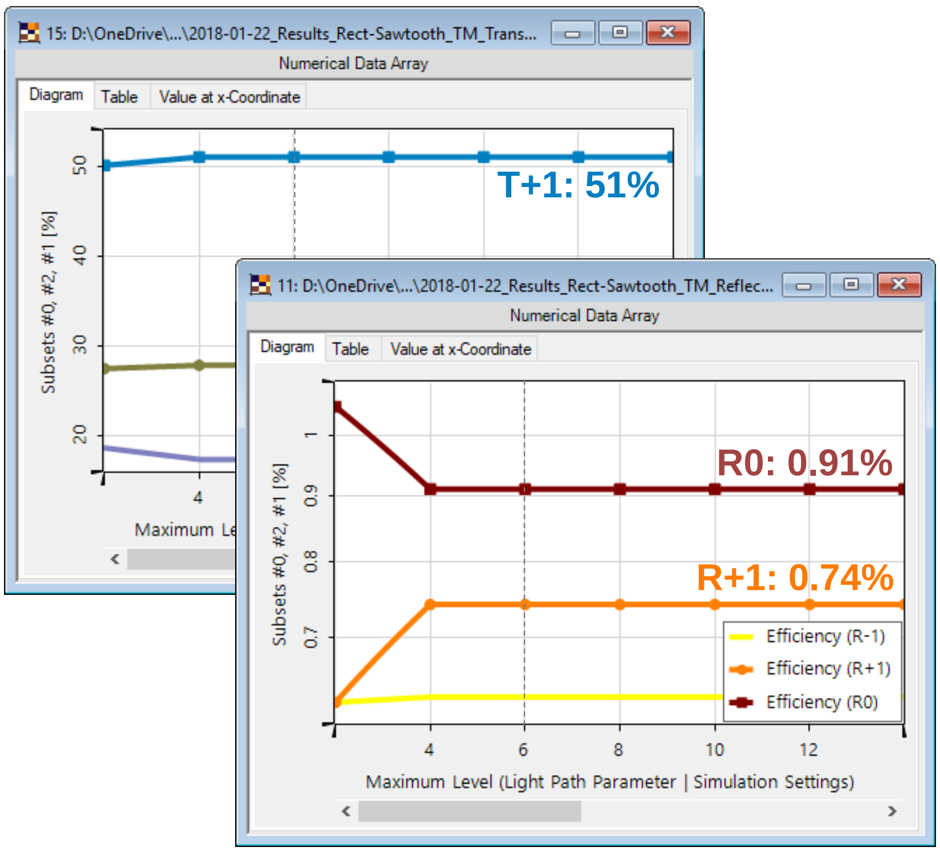



Global S matrix (TM)

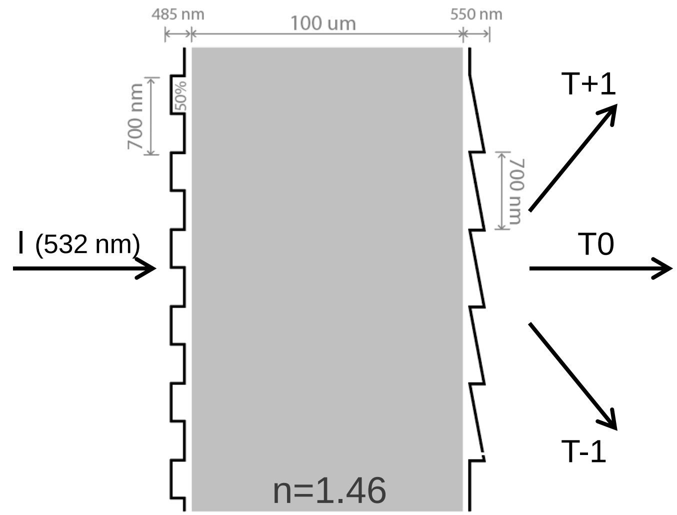
| T | Eff. | R | Eff. |
|---|---|---|---|
| -1 | 28.1% | -1 | 0.65% |
| 0 | 18.2% | 0 | 0.923% |
| +1 | 51.4% | +1 | 0.74% |

# Rectangular + Sawtooth Grating (parallel)

- Non-sequential field tracing




- ... with sawtooth coating

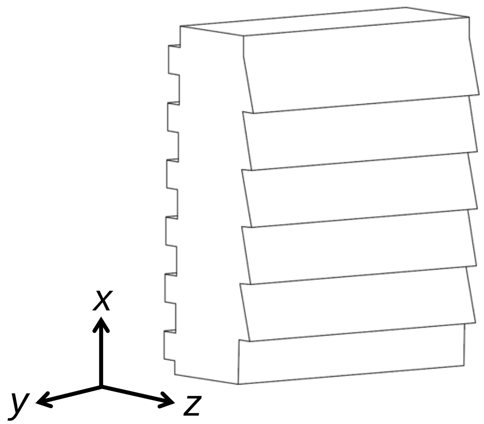



Global S matrix (TM)

| T | Eff. | R | Eff. |
|---|---|---|---|
| -1 | 28.1% | -1 | 0.65% |
| 0 | 18.2% | **0** | **0.923%** |
| +1 | 51.4% | **+1** | **0.74%** |

# Computational Effort

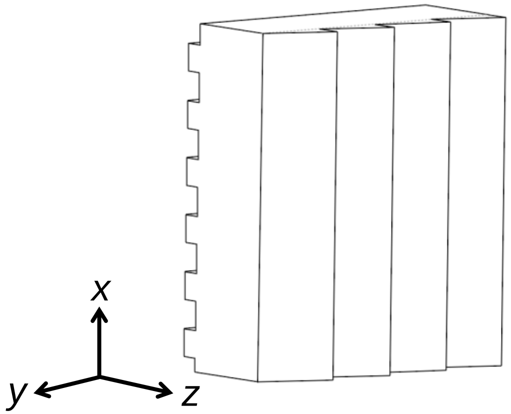
- Parallel gratings




| Global S matrix | Non-sequential field tracing |
|---|---|
| $\sim N^3$ (scaling with number of layers) | $\sim N^3$ (scaling with number of light paths) |

with $N$ as the number of diffraction (evanescent included) orders used in calculation

- Crossed gratings

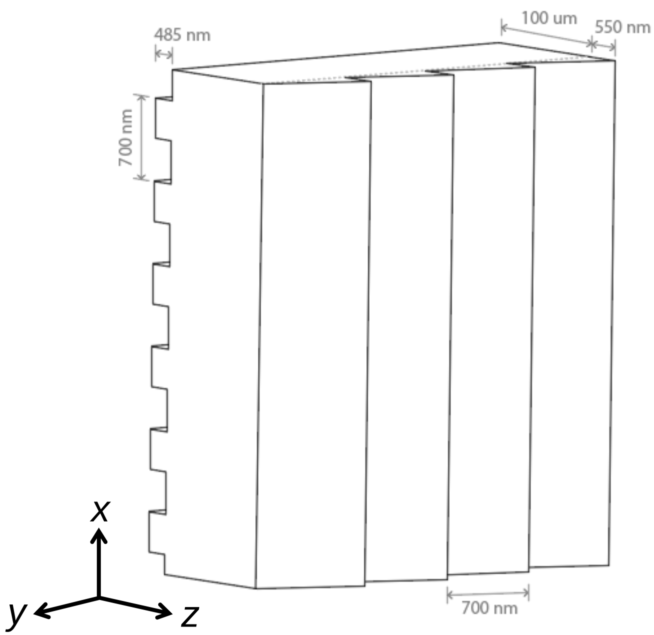


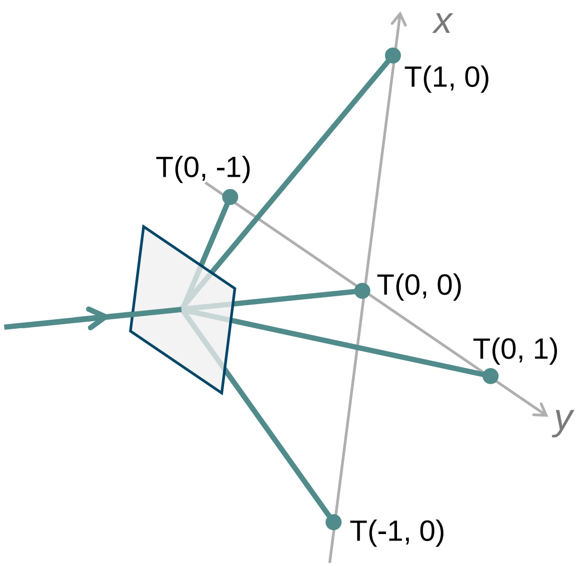

| Global S matrix | Non-sequential field tracing |
|---|---|
| $\boxed{\sim (N_x \times N_y)^3}$ (scaling with number of layers) | $\sim (N_x^3 + N_y^3)$ (scaling with number of light paths) |

with $N_x$ and $N_y$ as the number of diffraction (evanescent included) orders in both directions

# Rectangular + Sawtooth Grating (crossed)

- Structure
  - Front: rectangular grating
    (along *x* direction)
  - Back: sawtooth grating
    (along *y* direction)



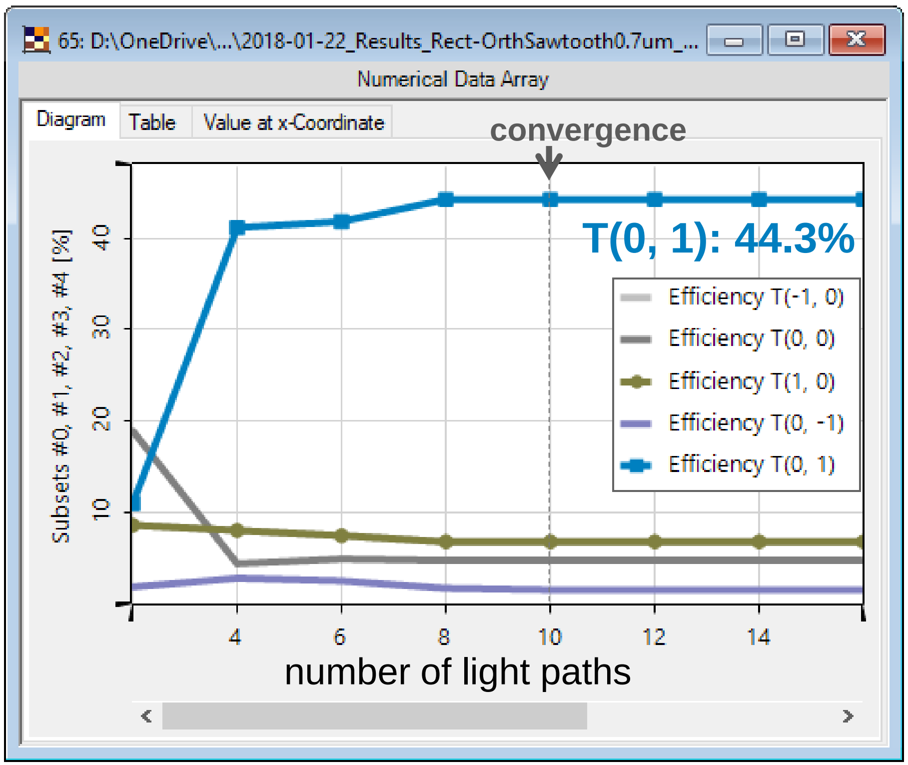



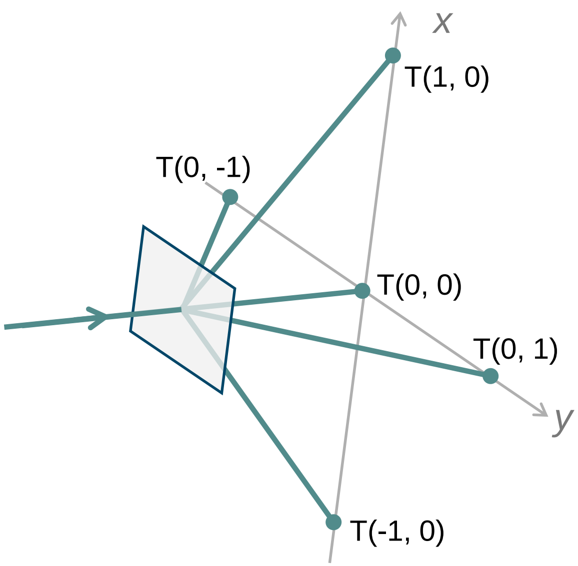

Global S matrix (TM)

| T | Eff. | R | Eff. |
|---|---|---|---|
| -1, 0 | 5.4% | -1, 0 | 5.7% |
| 0, -1 | 4.2% | 0, -1 | 5.8% |
| 0, 0 | 4.5% | 0, 0 | 13.8% |
| 0, 1 | 44.9% | 0, 1 | 4.6% |
| 1, 0 | 5.4% | 1, 0 | 5.7% |

# Rectangular + Sawtooth Grating (crossed)

- Non-sequential field tracing (TM)



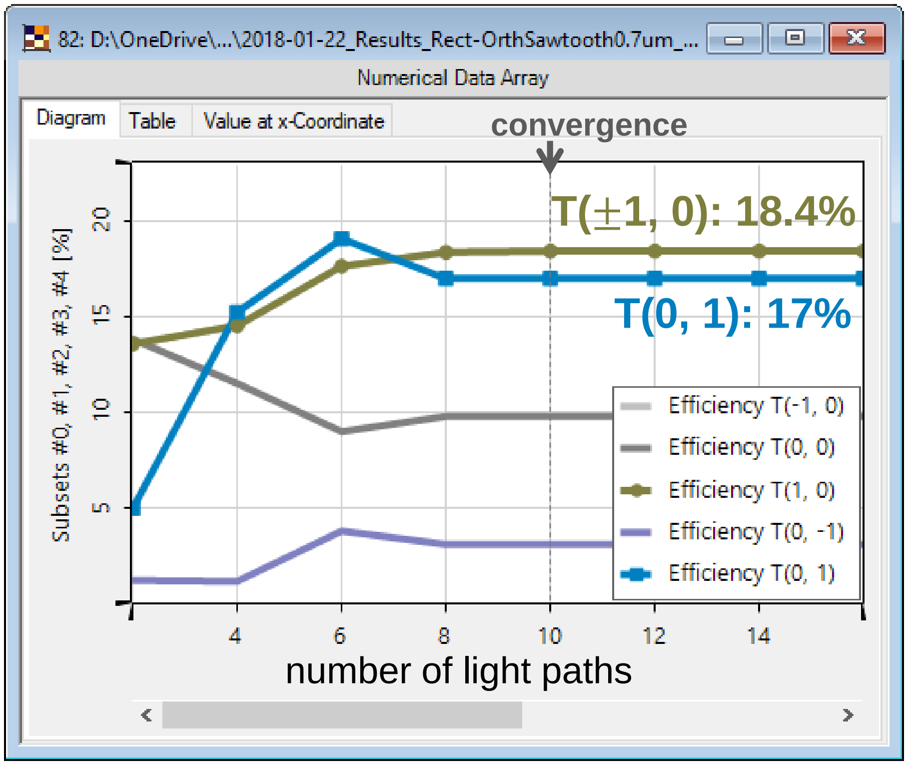



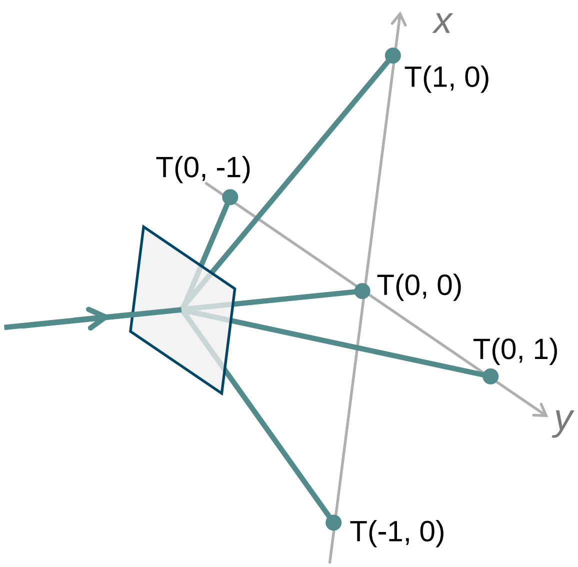

Global S matrix (TM)

| T | Eff. | R | Eff. |
|---|---|---|---|
| -1, 0 | 5.4% | -1, 0 | 5.7% |
| 0, -1 | 4.2% | 0, -1 | 5.8% |
| 0, 0 | 4.5% | 0, 0 | 13.8% |
| **0, 1** | **44.9%** | 0, 1 | 4.6% |
| 1, 0 | 5.4% | 1, 0 | 5.7% |

# Rectangular + Sawtooth Grating (crossed)

- Non-sequential field tracing (TE) **Polarization included!**



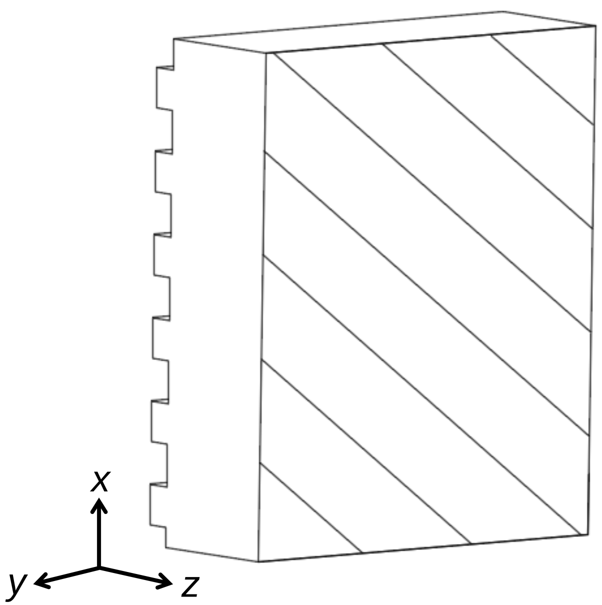



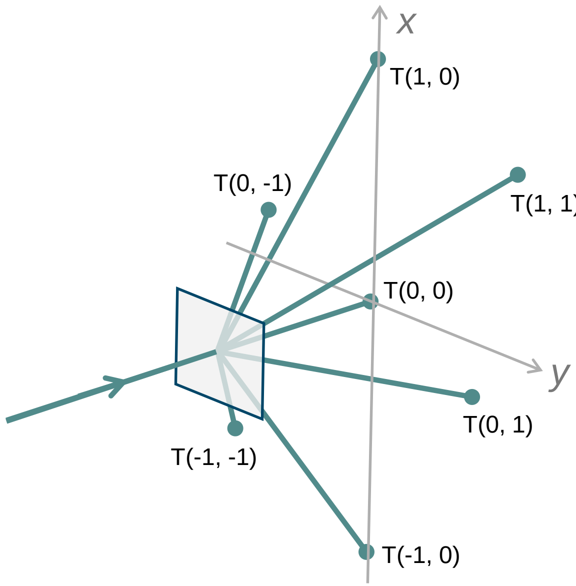

Global S matrix (TE)

| T | Eff. | R | Eff. |
|---|---|---|---|
| **-1, 0** | **18%** | -1, 0 | 1.1% |
| 0, -1 | 2.8% | 0, -1 | 0.46% |
| 0, 0 | 11.9% | 0, 0 | 22.6% |
| **0, 1** | **17.1%** | 0, 1 | 6.89% |
| **1, 0** | **18%** | 1, 0 | 1.1% |

# Rectangular + Sawtooth Grating (45° rotated)

- Structure
  - Front: rectangular grating
    (along *x* direction)
  - Back: sawtooth grating
    (along *x*-*y* diagonal direction)

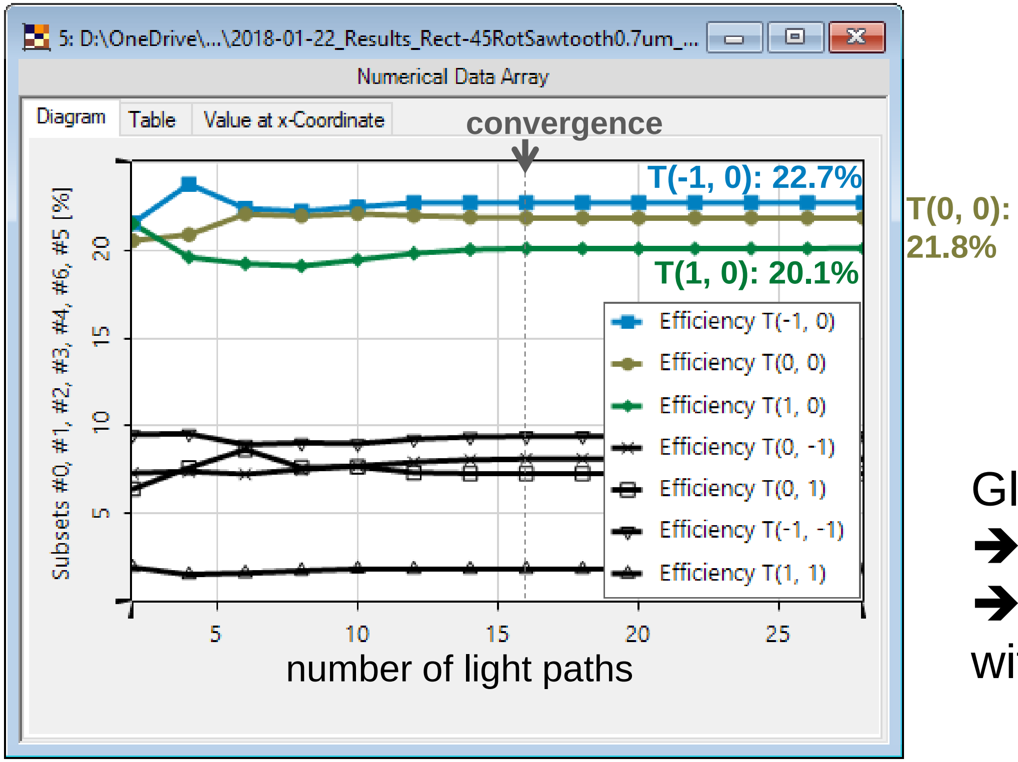


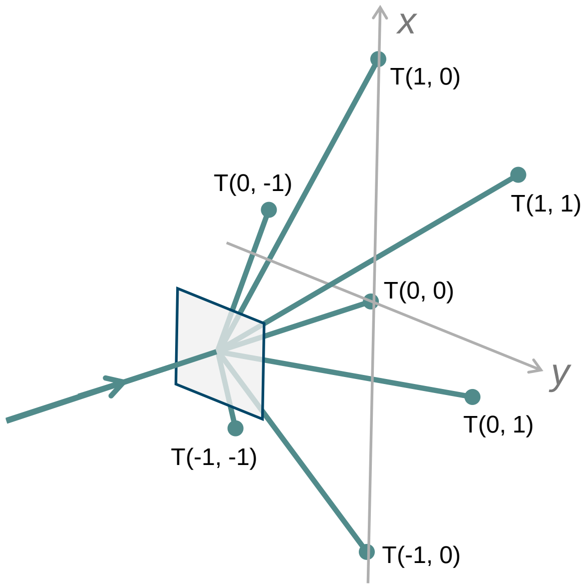




Global S matrix (TM)
➔ No common period!
➔ Huge computational effort even with approximated common period

# Rectangular + Sawtooth Grating (45° rotated)

- Non-sequential field tracing (TM)




Global S matrix ***NOT*** possible!
➔ No common period
➔ Huge computational effort even with approximated common period

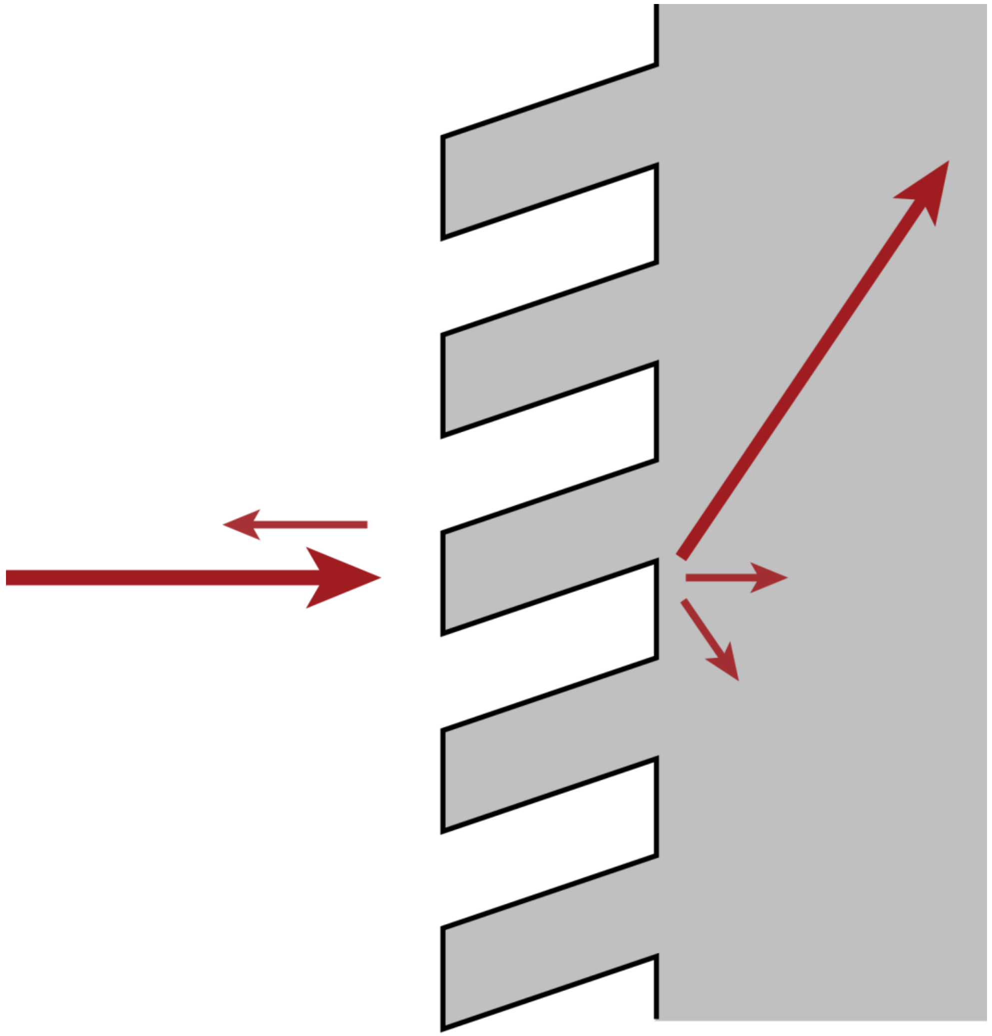
# Document & Technical Info

| | |
|---|---|
| code | |
| version of document | 1.0 |
| title | Coupled Surfaces Analysis by Using Non-sequential Field Tracing |
| category | Non-sequential Field Tracing |
| author | Site Zhang (LightTrans) |
| used VL version | 7.2.0.2 |

| **Specifications of PC Used for Simulation** | |
|---|---|
| Processor | i7-4910MQ (4 CPU cores) |
| RAM | 32 GB |
| Operating System | Windows 10 |

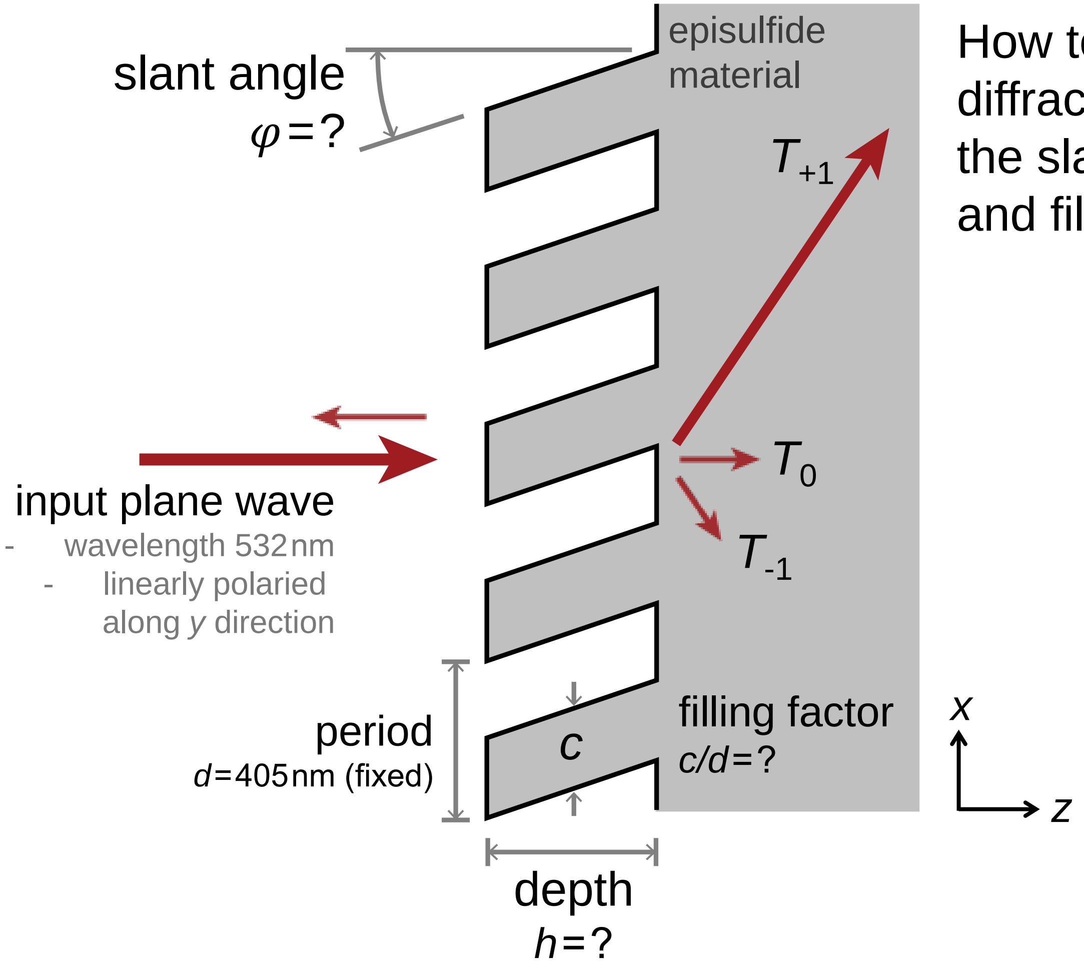
# Parametric Optimization and Tolerance Analysis of Slanted Gratings

# Abstract

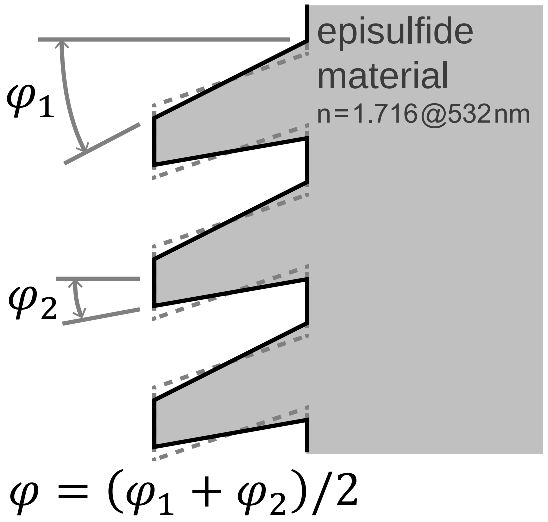


Coupling of light into guiding structures with high efficiency is an important issue for many applications, like backlight, optical interconnector, and near-to-eye displays. For such applications, slanted gratings are well known for being capable to couple monochromatic light with high efficiency. In this example, the optimization of a slanted grating with the rigorous Fourier modal method is presented. The optimized grating shows a diffraction efficiency of over 90% for a predefined direction order. In addition, the influence from the slope deviation of the grating is investigated.

# Modeling Task

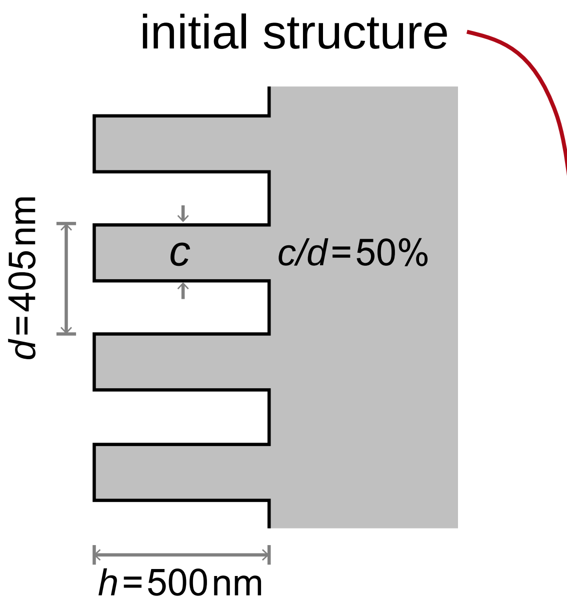



How to optimize the $T_{+1}$ order diffraction efficiency, by adjusting the slant angle $\varphi$, grating depth $h$, and filling factor $c/d$?

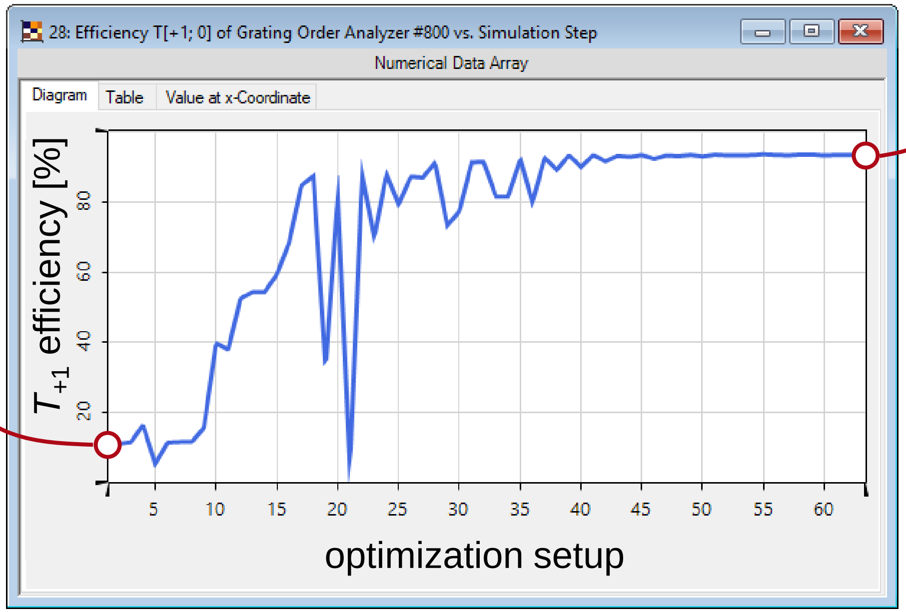



In addition, how to evaluate the grating performance with the slope deviation due to the fabrication technique taken into account?

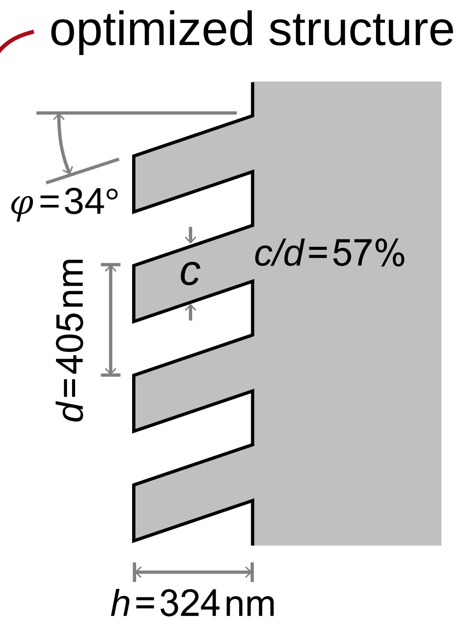
# Results – Parametric Optimization




| Order | Efficiency |
|---|---|
| -1 | 11.551% |
| 0 | 72.795% |
| +1 | 11.551% |



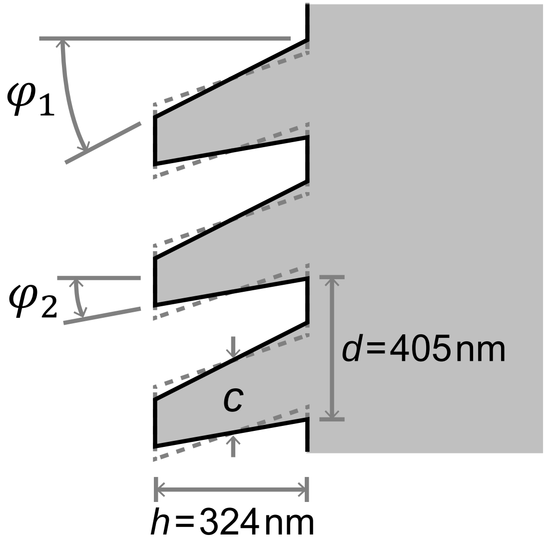

parametric optimization with rigorous Fourier modal method for grating efficiency calculation



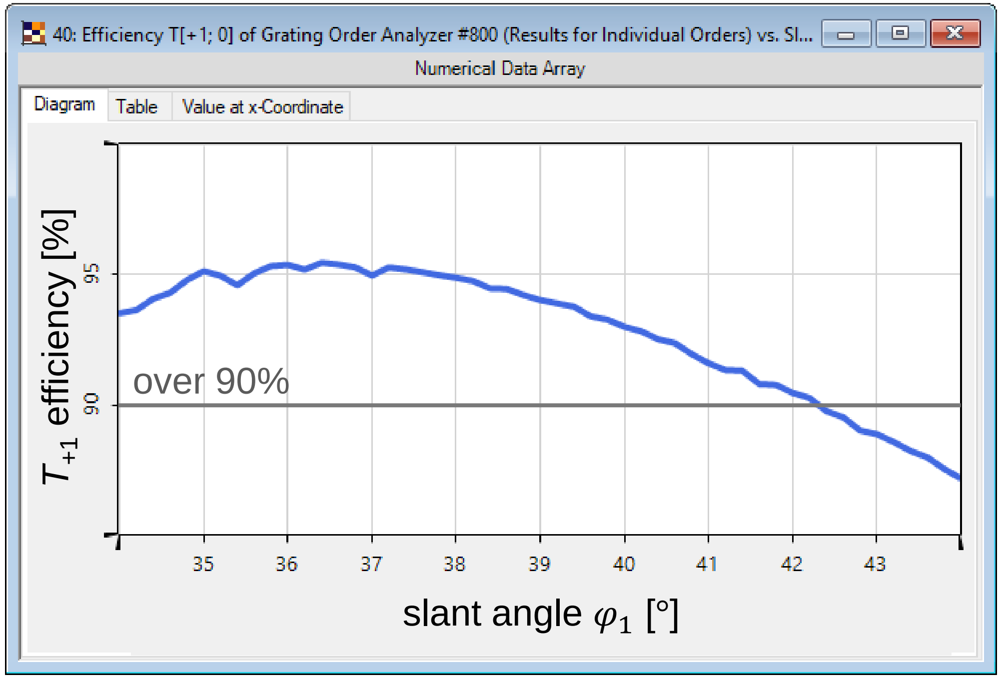

| Order | Efficiency |
|---|---|
| -1 | 0.267% |
| 0 | 6.027% |
| **+1** | **91.275%** |

# Results – Tolerance Analysis

The fabricated slanted gratings often shows a deviation from the perfect parallel grating lines. Such slope deviations should be taken into account for the tolerance analysis.




- fixed average slant angle $\varphi = (\varphi_1 + \varphi_2)/2 = 34°$
- fixed filling factor c/d=57%
- varying $\varphi_1$ from 34 to 44°




Rigorous simulation with Fourier modal method, for tolerance analysis over 50 steps, takes 30 seconds.

# Document Information

| | |
|---|---|
| title | Parametric Optimization and Tolerance Analysis of Slanted Gratings |
| version | 1.0 |
| VL version used for simulations | 7.3.0.48 |
| category | Application Use Case |