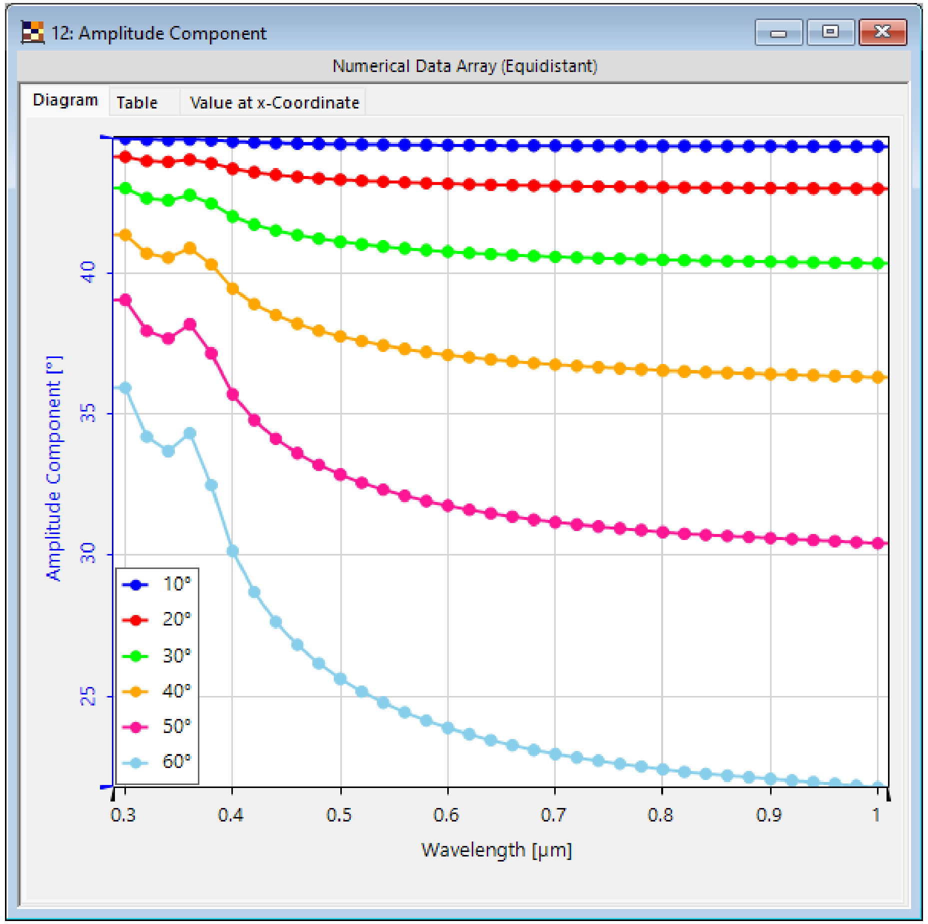
Ellipsometry Analyzer

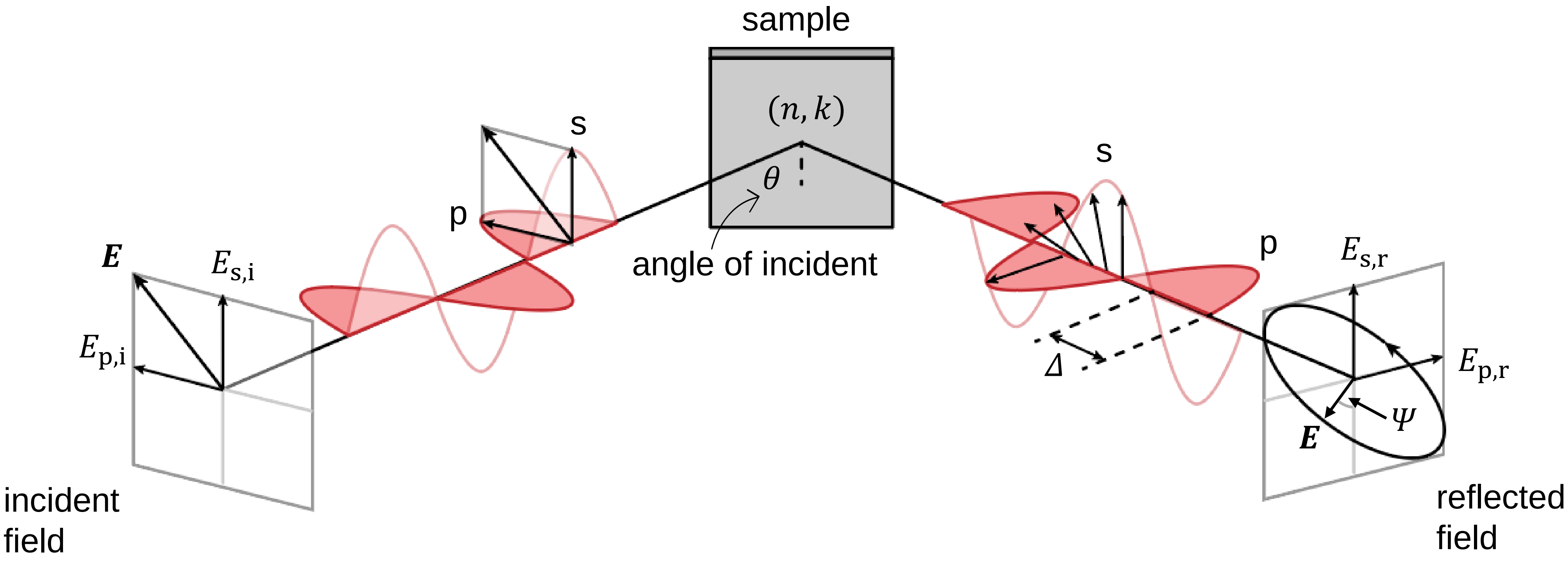
Abstract



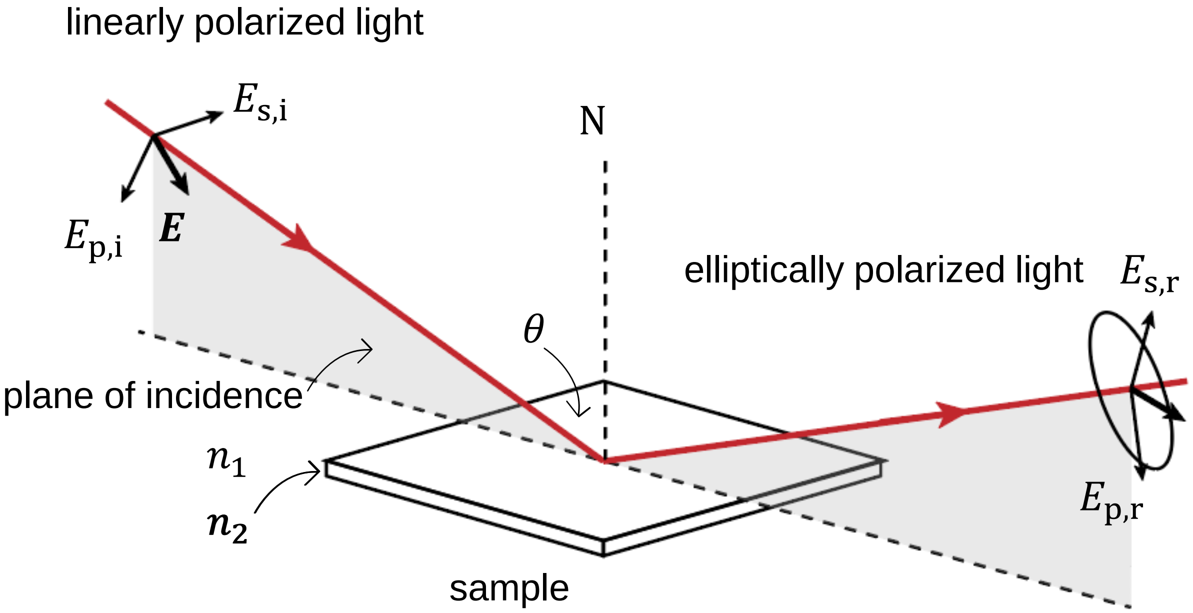
Ellipsometry is an optical measurement method which is commonly used to determine the dielectric properties of thin films. The measurement involves determining the change in the polarization state of light upon reflection or transmission from the sample, for different wavelengths and angles of incidence. Hence, it can be used to characterize the composition, roughness, thickness, crystalline properties, electrical conductivity, and other material properties. It is very sensitive to changes in the optical response of the incident radiation interacting with the material under study. This use case demonstrates the basic principles of ellipsometry and illustrates the use of the built-in ellipsometry analyzer in VirtualLab Fusion.

Basic Principle of Ellipsometry

When linear polarized light (decomposed into a wave polarized parallel ($E_{\mathrm{p,i}}$) and one perpendicular ($E_{\mathrm{s,i}}$) to the plane of incidence) interacts with a dielectric medium, the polarization state will change. From the resulting phase shift (Δ) between the impinging and reflected (or transmitted) wave, as well as the ratio of the reflected (or transmitted) amplitudes ($\tan(\Psi)$), the dielectric properties of the medium (n, k) can be derived.



Basic Principle of Ellipsometry



The aim of an ellipsometry measurement is to obtain the complex reflectance ratio ρ, which can be parametrized by the phase difference Δ and the amplitude component Ψ. Ellipsometry measures the reflection for the s- and p-component, which can be described as complex reflection (or Rayleigh in case of a grating) coefficients (R_p, R_s):

$$\rho = \frac{R_\mathrm{p}}{R_\mathrm{s}} = \tan(\Psi)\exp(i\Delta).$$

Hence, phase difference Δ and the amplitude component Ψ can be written as

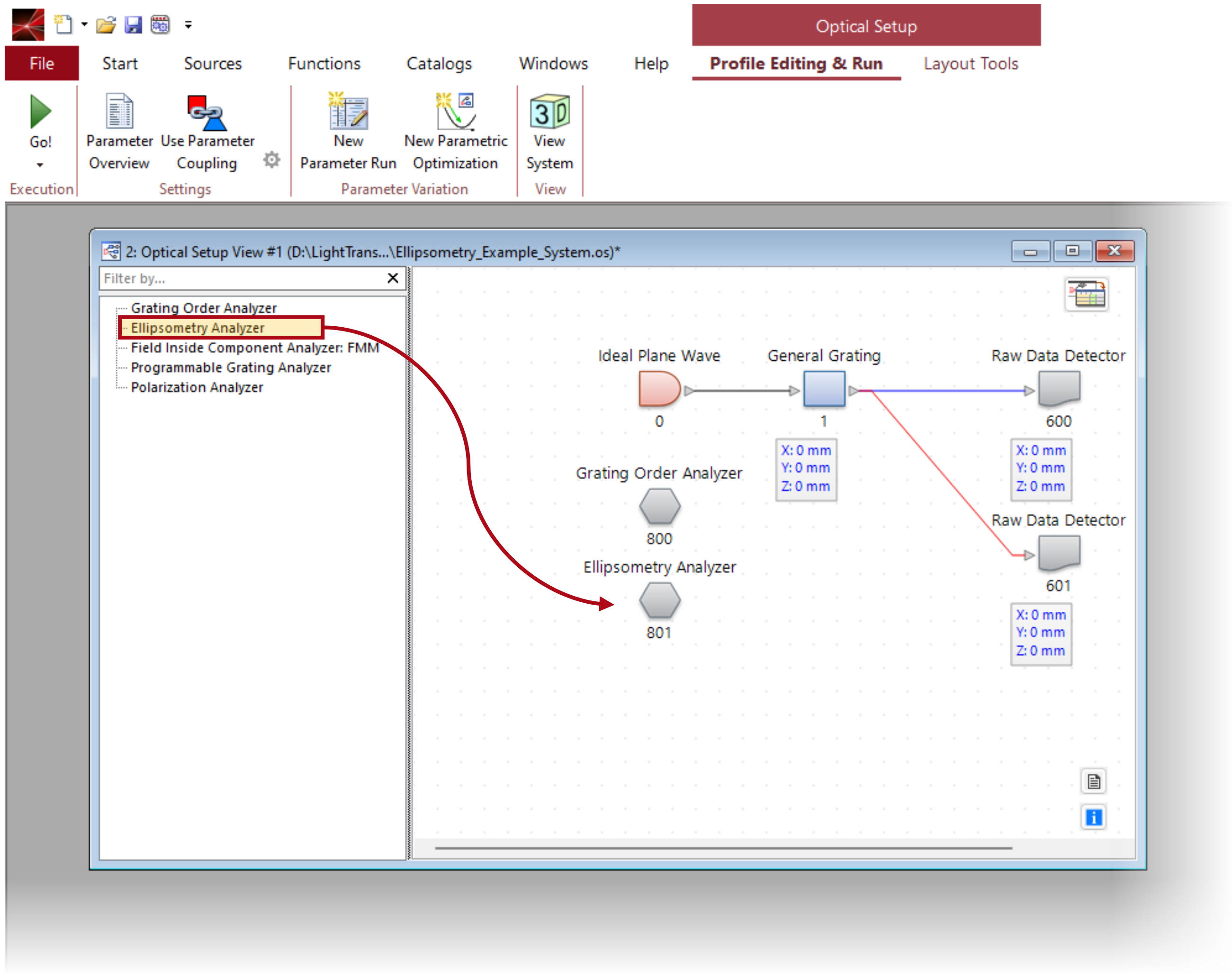
$$\Delta = \delta_\mathrm{p} - \delta_\mathrm{s}, \text{ and } \tan\Psi = \frac{|R_\mathrm{p}|}{|R_\mathrm{s}|},$$

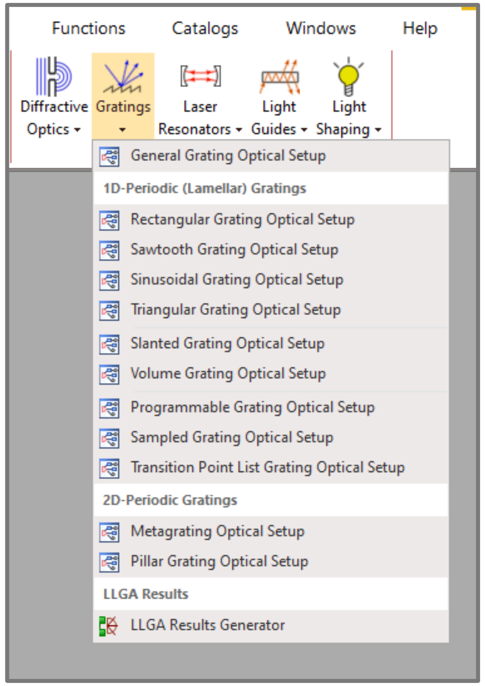
where δ_p and δ_s are the phase changes for the p- and s-polarized component after reflection, respectively.

After the determination of Δ and Ψ a model analysis must be performed, as the optical constants cannot be derived directly, in general. This analysis usually requires different types of models, depending on the type of material of the sample and will not be discussed in this example.

Note: Similar considerations apply to the transmission case, but for sake of simplicity only reflection is discussed.

Adding the Ellipsometry Analyzer to the System





The Ellipsometry Analyzer can be found in the menu of any *Grating Optical Setup* and be added to the system by drag & drop. Please note that the analyzer will only function if a stack is defined in the corresponding grating component (see: Configuration of Grating Structures by Using Interfaces).

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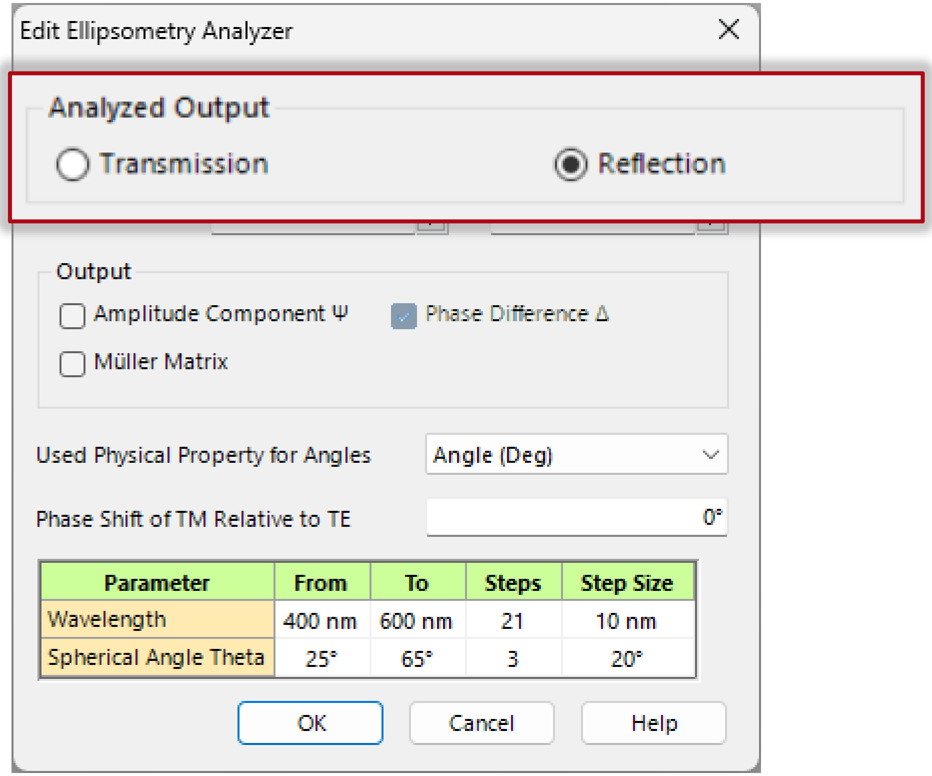
Analyzed Output



Analyzed Output

○ Transmission ● Reflection

Output

☐ Amplitude Component Ψ ☑ Phase Difference Δ

☐ Müller Matrix

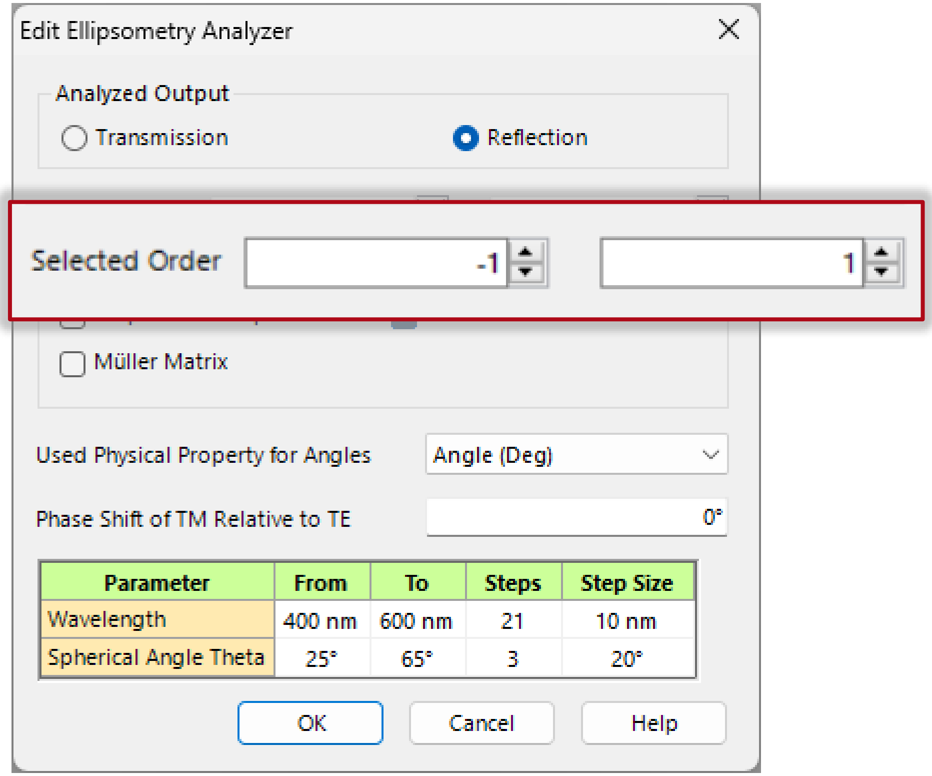
Used Physical Property for Angles: Angle (Deg)

Phase Shift of TM Relative to TE: 0°

Parameter	From	To	Steps	Step Size
Wavelength	400 nm	600 nm	21	10 nm
Spherical Angle Theta	25°	65°	3	20°

- The *Ellipsometry Analyzer* can either calculate the results for *Reflection* or *Transmission* of light at the defined stack.
- This stack can comprise of a single or a certain number of layers, or a 1D or 2D-periodic structure (grating).
- The analyzer configures the orientation and positions of *Optical Setup* during a calculation. Hence, it is not required to configure either the positions of the light source, detectors in the optical system or the polarization state of light in the source.

Order Selection



Analyzed Output

○ Transmission ● Reflection

Selected Order -1 1

☐ Müller Matrix

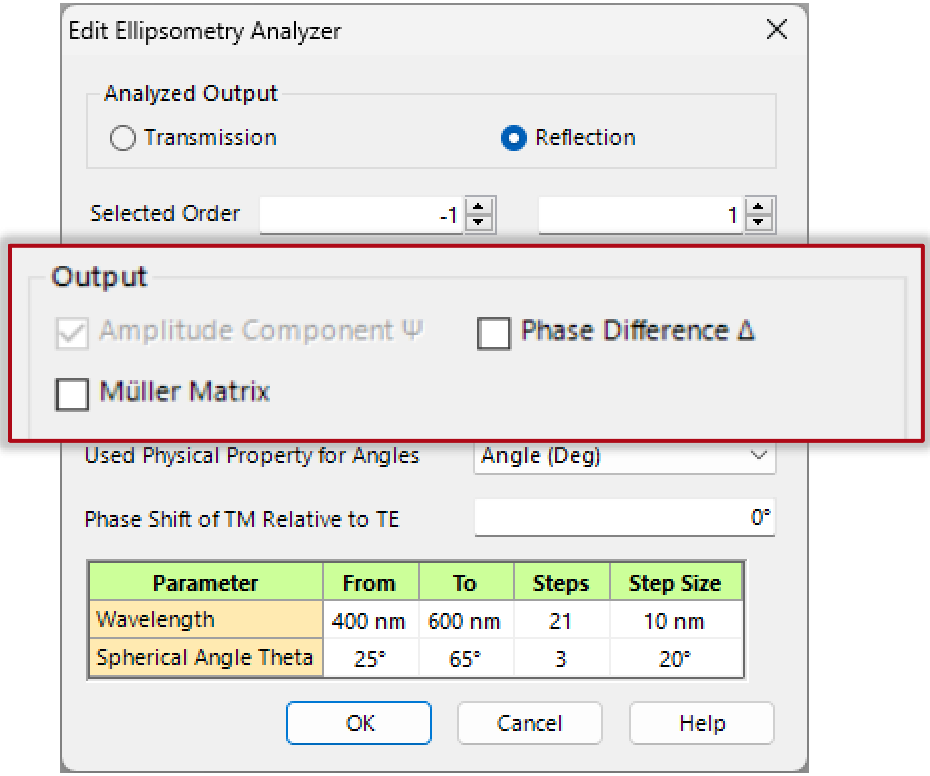
Used Physical Property for Angles: Angle (Deg)

Phase Shift of TM Relative to TE: 0°

Parameter	From	To	Steps	Step Size
Wavelength	400 nm	600 nm	21	10 nm
Spherical Angle Theta	25°	65°	3	20°

- For a layer stack, without lateral periodicity the order (0,0) should be chosen.
- If a grating structure is used as sample, the considered diffraction order can be selected, by defining the index of the investigated order in x and y.
- In case of a 1D-periodic gratings the second index should be zero.

Output



Analyzed Output

○ Transmission ● Reflection

Selected Order: -1, 1

Output

☑ Amplitude Component Ψ ☐ Phase Difference Δ

☐ Müller Matrix

Used Physical Property for Angles: Angle (Deg)

Phase Shift of TM Relative to TE: 0°

Parameter	From	To	Steps	Step Size
Wavelength	400 nm	600 nm	21	10 nm
Spherical Angle Theta	25°	65°	3	20°

Available Outputs:

- Amplitude component Ψ and phase difference Δ, defined by:

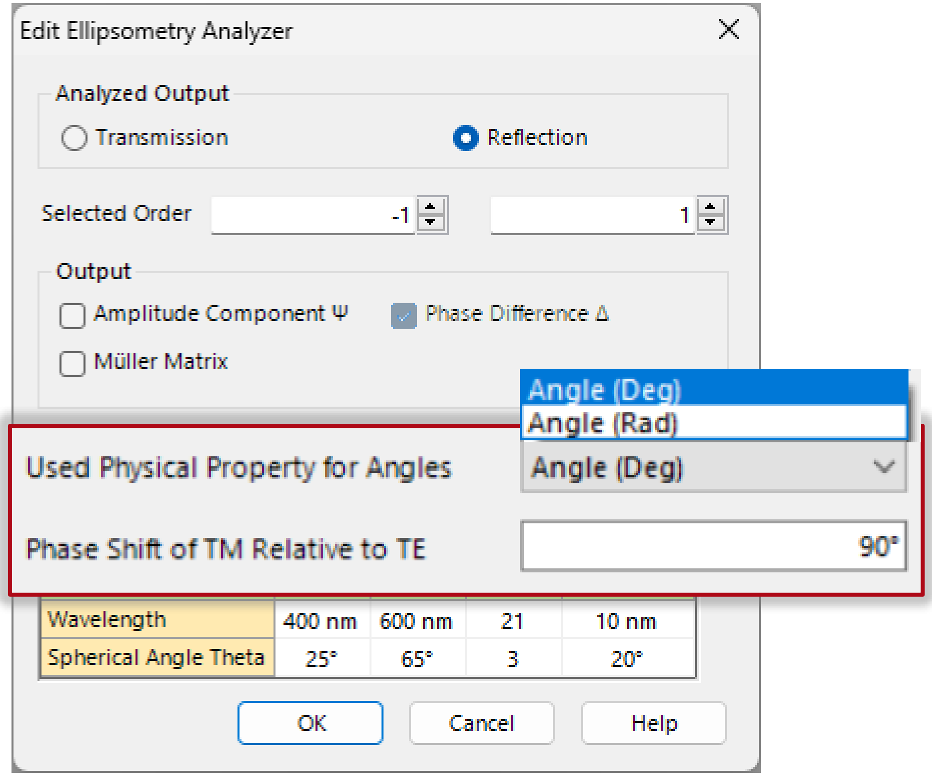
$$\frac{R_\mathrm{p}}{R_\mathrm{s}} = \tan(\Psi)\exp(i\Delta)$$

- The resulting entries of the Müller matrix $\mathcal{M}$, that describe the transformation of the Stokes parameters by the analyzed element:

$$\mathcal{M} = \begin{pmatrix} \frac{1}{2}(A_\mathrm{p}+A_\mathrm{s}) & \frac{1}{2}(A_\mathrm{p}-A_\mathrm{s}) & 0 & 0 \\ \frac{1}{2}(A_\mathrm{p}-A_\mathrm{s}) & \frac{1}{2}(A_\mathrm{p}+A_\mathrm{s}) & 0 & 0 \\ 0 & 0 & A_\mathrm{p}\cdot A_\mathrm{s}\cdot\cos(\Delta) & A_\mathrm{p}\cdot A_\mathrm{s}\cdot\sin(\Delta) \\ 0 & 0 & -A_\mathrm{p}\cdot A_\mathrm{s}\cdot\cos(\Delta) & A_\mathrm{p}\cdot A_\mathrm{s}\cdot\cos(\Delta) \end{pmatrix}$$

with $R_\mathrm{p} = A_\mathrm{p}\mathrm{e}^{i\phi_p}$ und $R_\mathrm{s} = A_\mathrm{s}\mathrm{e}^{i\phi_s}$

Angle Definition



Edit Ellipsometry Analyzer

Analyzed Output

○ Transmission ● Reflection

Selected Order -1 1

Output

☐ Amplitude Component Ψ ☑ Phase Difference Δ

☐ Müller Matrix

Used Physical Property for Angles: Angle (Deg)

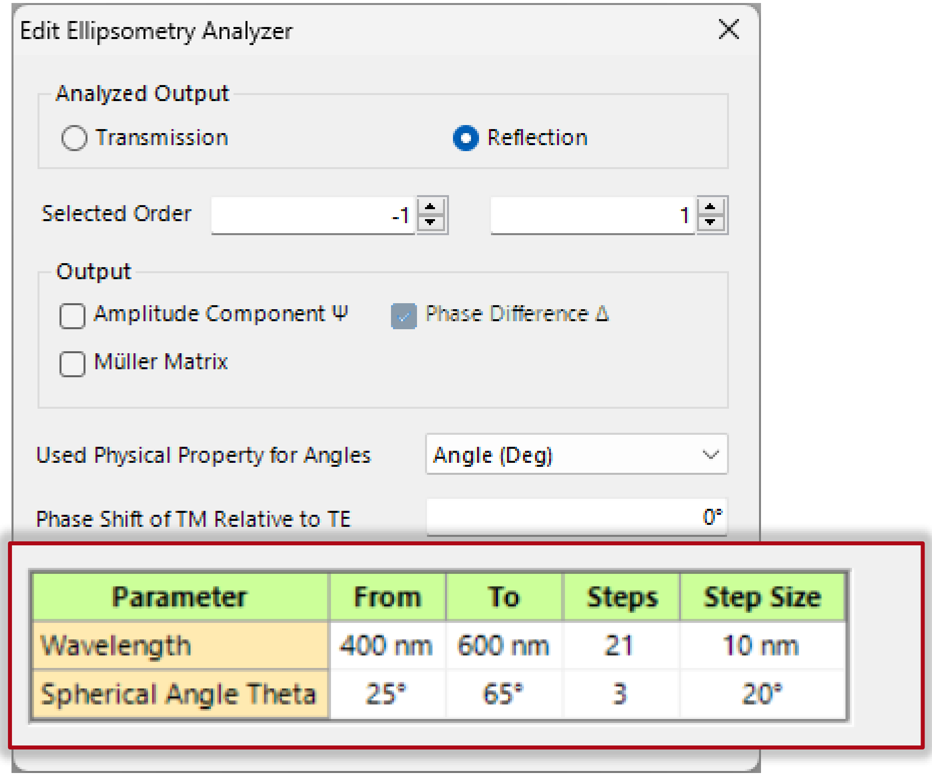
Phase Shift of TM Relative to TE: 90°

Wavelength	400 nm	600 nm	21	10 nm
Spherical Angle Theta	25°	65°	3	20°

- The angle of incidence can either be defined in degree (*Deg*) or radian (*Rad*).

- The *Phase Shift of TM Relative to TE* is a phase shift compensator that - if introduced into the ellipsometry analysis - will only shift the relative phase difference between p- and s-polarizations (Δ) and will have no impact on the actual amplitudes of the p- and s-polarized components (Ψ).

Sweep of Wavelength & Angle of Incidence



Edit Ellipsometry Analyzer

Analyzed Output

○ Transmission ● Reflection

Selected Order -1 1

Output

☐ Amplitude Component Ψ ☑ Phase Difference Δ

☐ Müller Matrix

Used Physical Property for Angles: Angle (Deg)

Phase Shift of TM Relative to TE: 0°

Parameter	From	To	Steps	Step Size
Wavelength	400 nm	600 nm	21	10 nm
Spherical Angle Theta	25°	65°	3	20°

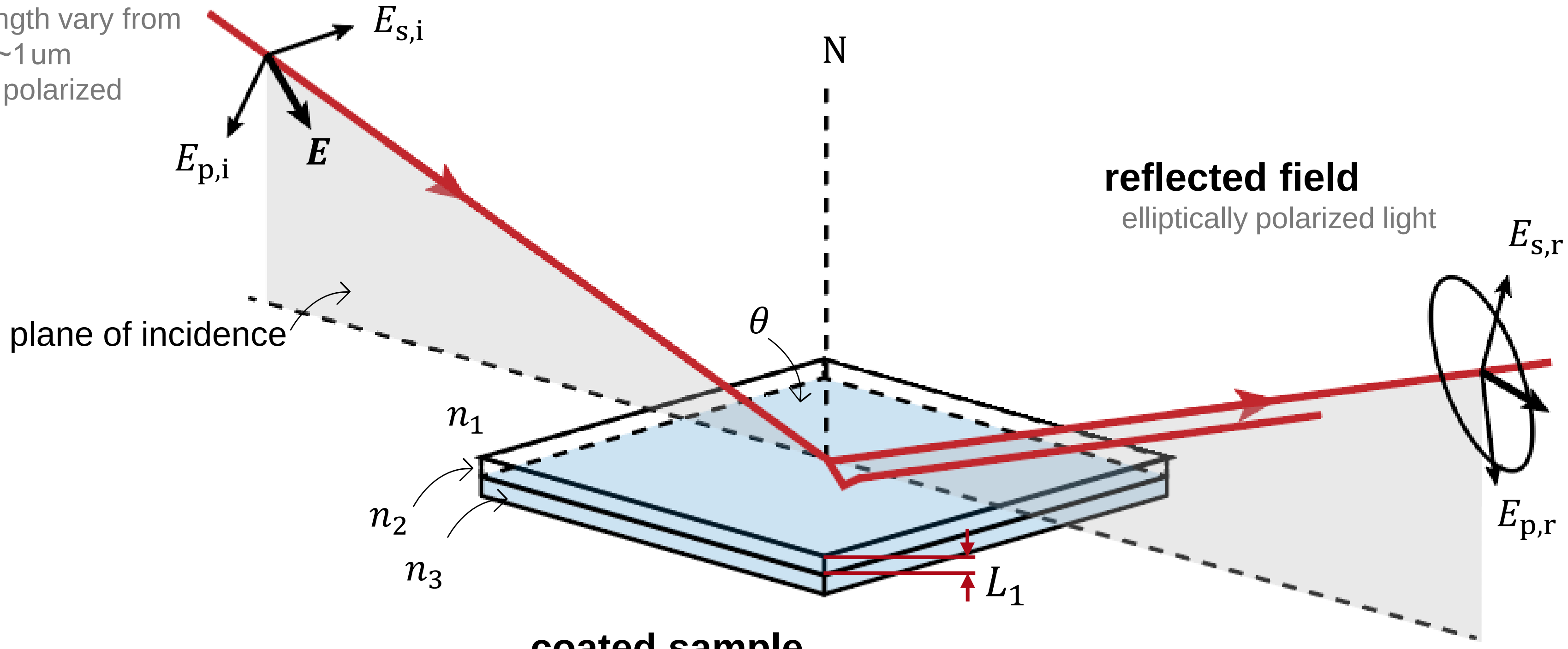
- The *Ellipsometry Analyzer* includes an option for a parameter sweep of the wavelength and angle of incidence by defining the range, step size and number of steps of the variation.
- Please note, that the range of wavelength of the sweep must be within the range of wavelength of the material definitions by which the sample is defined.

Example System

Parameters follow from Woollam et al., Proc. SPIE 10294, 1029402 (1999)

input field

- ideal plane wave
- wavelength vary from 200 nm~1 um
- linearly polarized



reflected field

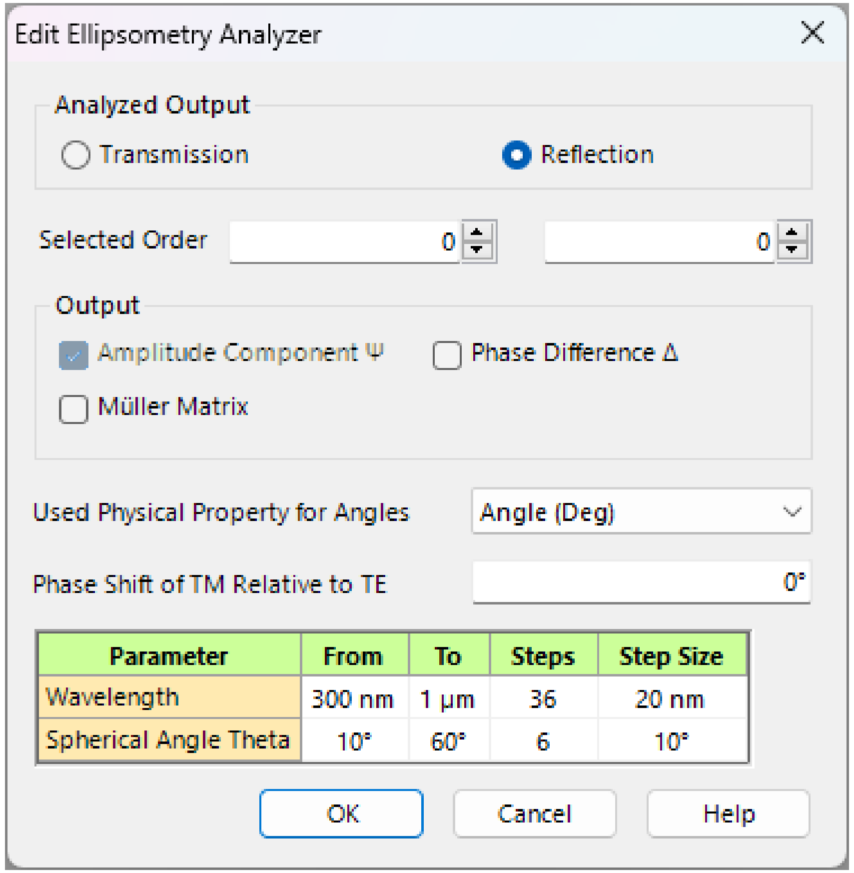
elliptically polarized light

coated sample

- coating: SiO2 thin film
- thickness L_1 : 10 nm
- base material: Si

See the full Use Case: Variable Angle Spectroscopic Ellipsometry (VAS) Analysis of a SiO2-Coating

Example Output of the Analyzer



Edit Ellipsometry Analyzer

Analyzed Output

○ Transmission ● Reflection

Selected Order 0 0

Output

☑ Amplitude Component Ψ ☐ Phase Difference Δ

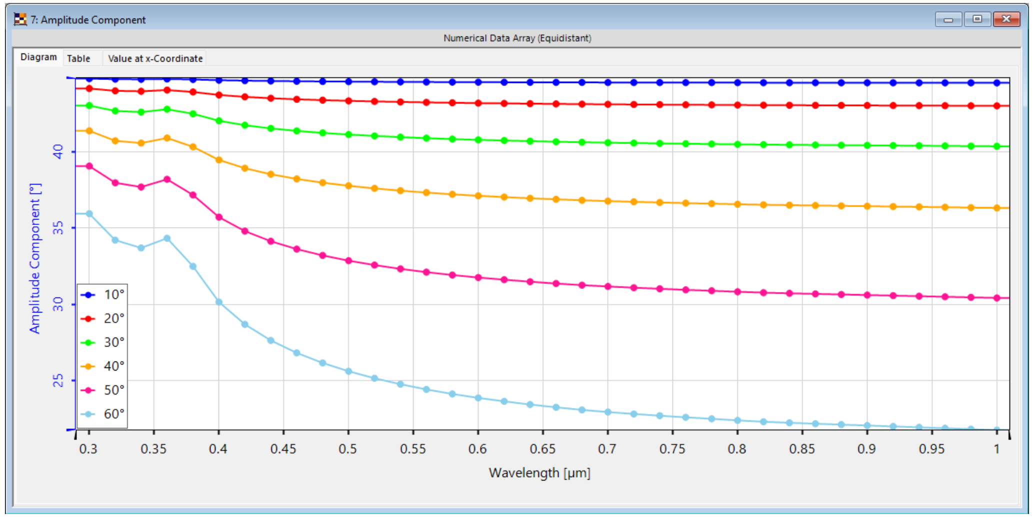
☐ Müller Matrix

Used Physical Property for Angles: Angle (Deg)

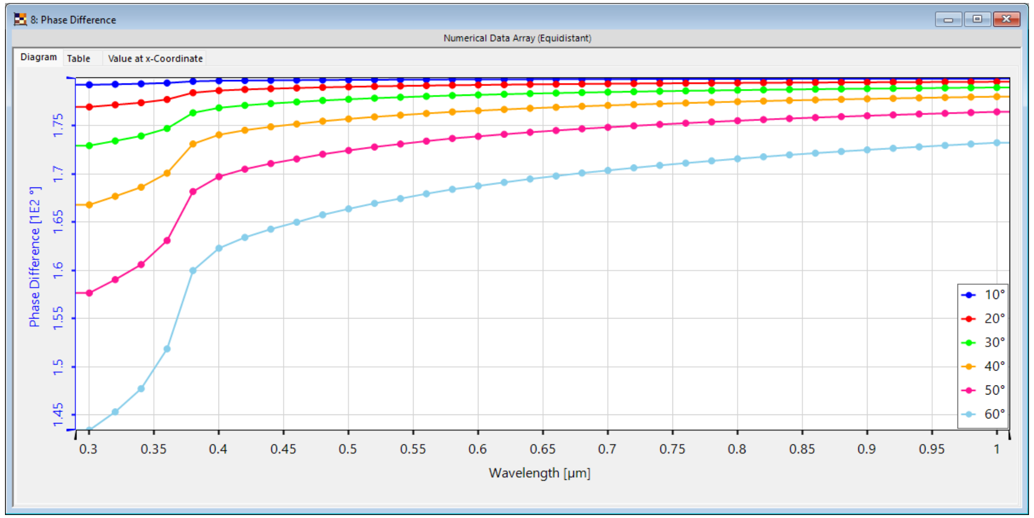
Phase Shift of TM Relative to TE: 0°

Parameter	From	To	Steps	Step Size
Wavelength	300 nm	1 µm	36	20 nm
Spherical Angle Theta	10°	60°	6	10°

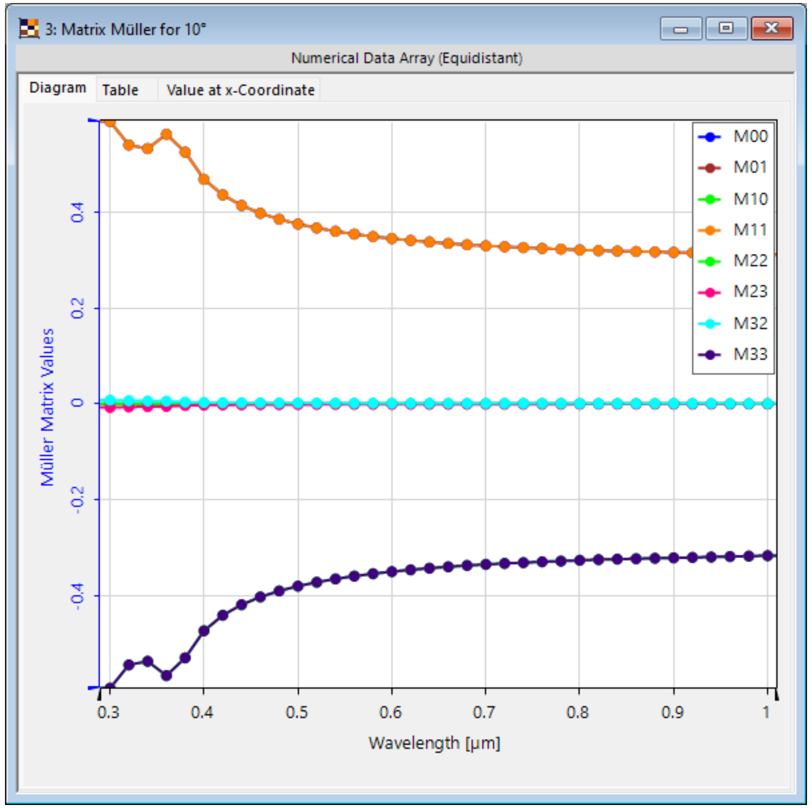
Ψ



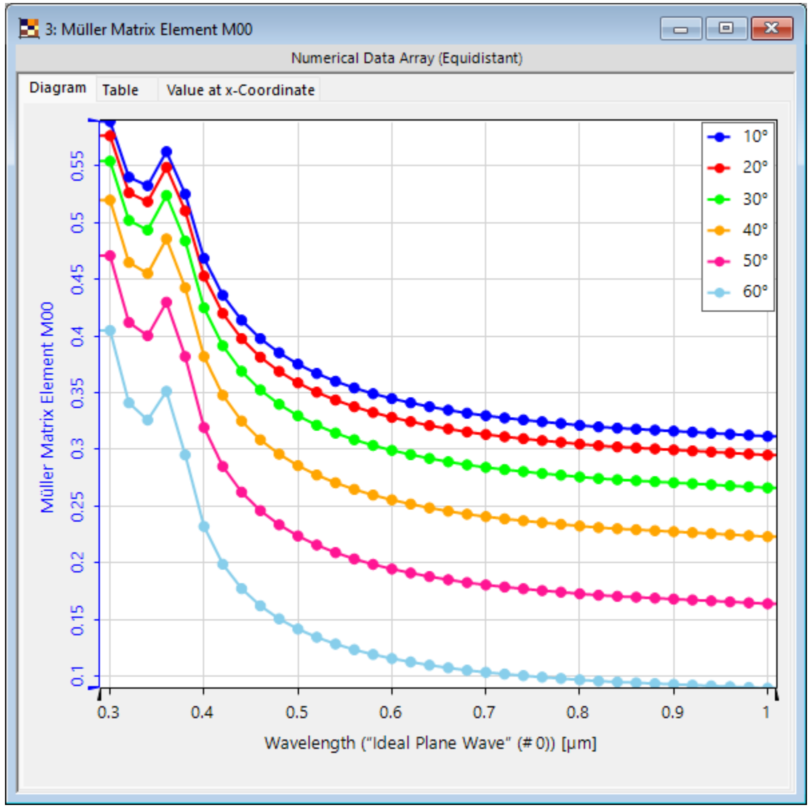
Δ



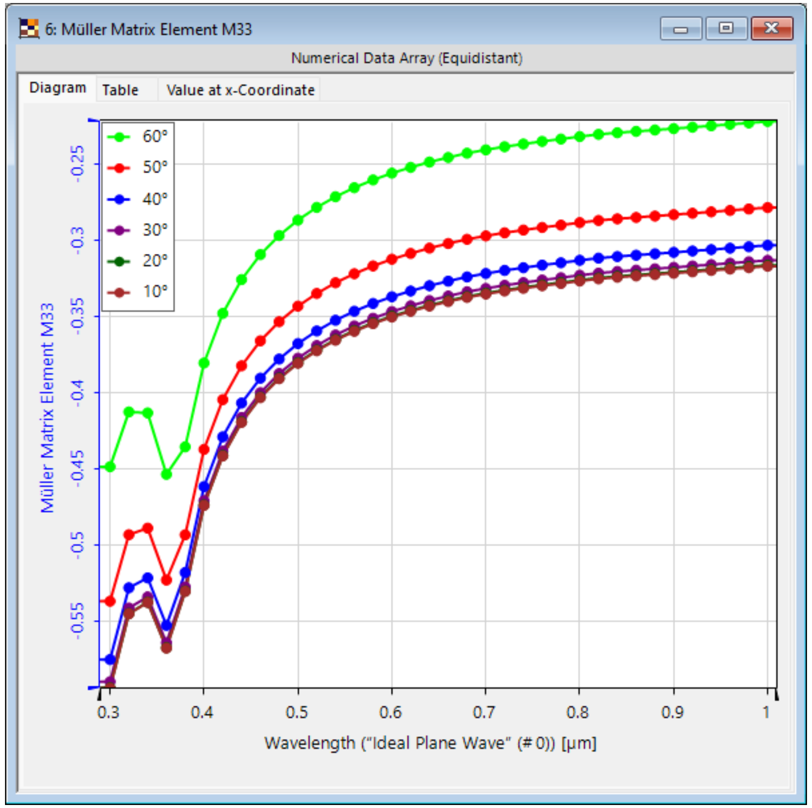
Example Output of the Analyzer – Müller Matrix



Müller matrix for 10°



Müller matrix element M00 for 10° - 60°



Müller matrix element M33 for 10° - 60°

Document Information

title	Ellipsometry Analyzer
document code	SWF.0019
document version	1.1
software edition	VirtualLab Fusion Advanced
software version	2023.1 (Build 1.556)
category	Feature Use Case
further reading	• *Variable Angle Spectroscopic Ellipsometry (VAS) Analysis of a SiO2-Coating*