

### **Quarter-Wave Plate Mirror**

**Educational Tutorial** 

## Why Educational Tutorials?

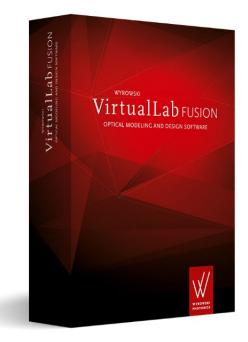
#### Learn software and physics — enjoyably and effectively.

Our hands-on tutorials are designed to make learning *VirtualLab Fusion* both engaging and efficient.

The fastest way to learn something new is by doing it yourself, especially when guided by a good example. These tutorials offer a practical, stepby-step approach that works even with the **trial license**.

You'll not only become familiar with the software, but also gain valuable insights into the underlying physics, making the tutorials ideal for **self-study, teaching**, and as a starting point for **engineers** and **scientists** exploring the software's possibilities.

Real, working examples bring abstract concepts to life far more effectively than just reading about features in a manual. And by the end, you'll feel confident enough to start building your own simulations.



### **Educational Tutorial #2 – Quarter-Wave Plate Mirror**

#### **Advancing Your Software Skills**

In this tutorial, we'll design a quarter-wave plate (*QWP*) mirror, building on the concepts from the first educational tutorial on the <u>Fabry-Pérot Interferometer</u>.

We'll move through the basic steps more quickly, assuming you're already familiar with:

- building Optical Setups,
- using the Light Path Finder,
- and the *Parameter Run* tool.

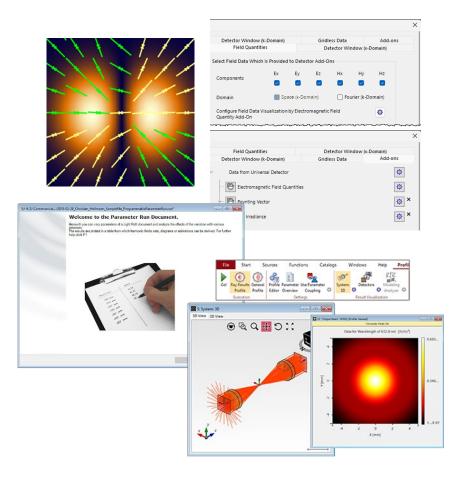
If you encounter any difficulties, we strongly recommend revisiting the first tutorial for a clearer understanding.

### **Educational Tutorial #2 – Quarter-Wave Plate Mirror**

#### Main New Concepts in Tutorial #2:

- Polarization Ellipses
- Programmable Detector Add-on
- 2D Parameter Run
- Parameter Optimization

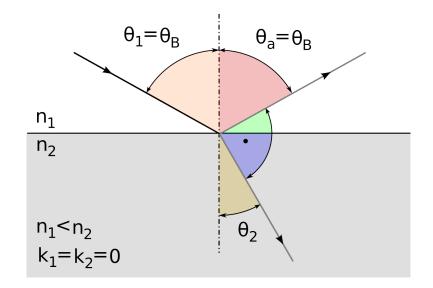
By the end, you'll deepen your understanding and feel more confident using the software for your own simulations.



#### **Physics background**

At the interface of two media with different refractive indices, *p*- and *s*-polarized light exhibit different reflection coefficients. This effect is most pronounced at the *Brewster Angle*, where *p*-polarized light is fully transmitted, leaving the reflected light purely *s*-polarized.

We will leverage this principle to design a mirror that transforms linearly polarized light into circularly polarized light, effectively acting as a quarter-wave plate, without requiring birefringent materials.



For non-absorbing media, the Brewster angle is given by

$$\theta_B = \tan^{-1}(n_2/n_1)$$

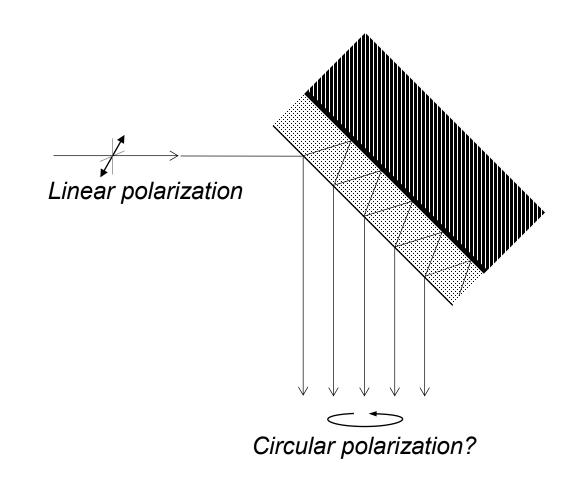
### **Overview**

The *QWP* mirror will consist of an ideal reflector coated with a thin, glass-like layer. Partial reflections at the front surface create different paths that all eventually reach the detector.

At the air-glass interface, the reflection coefficients differ for *s*and *p*-polarized light, giving their paths different "weights" or strengths. As a result, both polarizations experience different phase delays on average. However, the total amount of *s*- and *p*-polarized light remains the same.

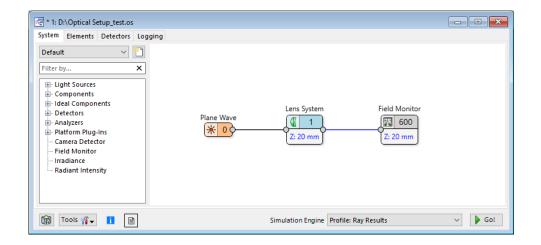
Circularly polarized light requires *s*- and *p*-polarized waves of equal amplitude with a 90° phase difference. To achieve this, the linear polarization direction of the incident light must be at 45° to the reflection plane, ensuring equal *s*- and *p*-components, while the coating provides the necessary 90° phase shift.

In the first test, light hits the mirror at a 45° angle, and the coating thickness is adjusted. But in this setup, it's not possible to create a 90° phase shift. A more detailed study shows that the phase shift can be achieved at larger angles of incidence.



### **Optical Setup**

- Start a new Optical Setup in VLF
- Add a *Plane Wave* source, a *Lens System*, and a *Field Monitor*
- Set all z-distances to 20 mm



	1: D:\Op	tical Setup test.os	-						×
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	600	Field Monitor							
<									>
<	Teal	· ⁄/ 1 🖹			ciente	tion Engine Profile: Ray Re			<b>&gt;</b> Go!

- Go to the *Detectors* tab
- Set Reference Type from (T) to Reflective (R)
  - The detector will auto-align along the specular reflection axis of the lens system

## **Optical Setup – Source**

• Double click on the *Plane Wave* icon

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• Set *Wavelength* to 500 nm

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Spectral Values			
Wavelength	500 nm Weig	ht	
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## **Optical Setup – Source**

• Set the linear polarization to 45°

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Angle	45°
Normalized Jones Vector	
$\begin{pmatrix} J_X \\ J_Y \end{pmatrix} = \begin{pmatrix} \end{pmatrix}$	0.70711
Default Parameters	
Validity: 🕑	OK Cancel Help

• Set *Diameter* to 5 mm x 5 mm

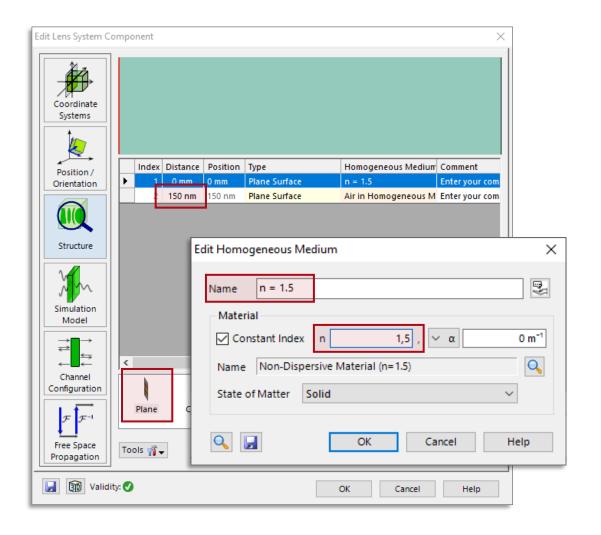
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<ul> <li>Automatic Setting</li> <li>Manual Setting</li> <li>Shape</li> <li>Diameter</li> <li>Relative Edge Width</li> </ul>	✓ A	gular	Ellip	tic 5 mn 10 9

# **Optical Setup – Mirror Coating**

The mirror consists of two surfaces with a medium between them.

- Edit Lens System
- Drag & drop two plane surfaces into the system.
- Edit the *Homogeneous Medium* behind the first surface
- Change the Name
- Choose *Defined by Constant Refractive Index* and set the value to 1.5
- Set the distance of the second surface to the first surface to 150 nm

This creates a 150 nm thick layer of material with n = 1.5 between the surfaces.

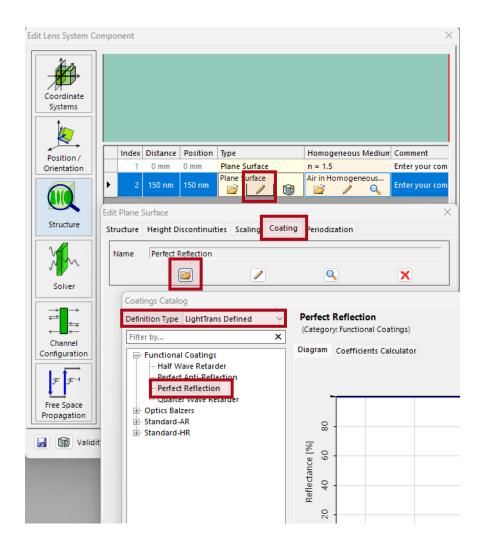


## **Optical Setup – Mirror Substrate**

Make the mirror substrate perfectly reflective:

- Edit the second Plane Surface
- Go to the *Coating* tab
- Click the *folder* icon to load a coating
- Set Definition Type to LightTrans Defined
- Under *Functional Coatings*, select *Perfect* Reflection (Click the *pencil* icon to view its properties, if desired)
- Click OK three times to apply and close all dialogs

Note that the medium behind the second surface has no further effect.



## **Optical Setup – Channel Configuration**

- Click the *cogwheel* ( ) icon in the *Light Path Finder*
- Set Channel Configuration Option to Manual
- Click OK

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🛃 * 1: Optical Setup								
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Tools <sup>™</sup> ↓				Simulation Eng				
					🐼 Assistant	OK	Cancel	Help

- Edit the Lens System
- Select Channel Configuration
- For *Surface # 1*, select all channels
- For *Surface # 2*, select the +/- channel

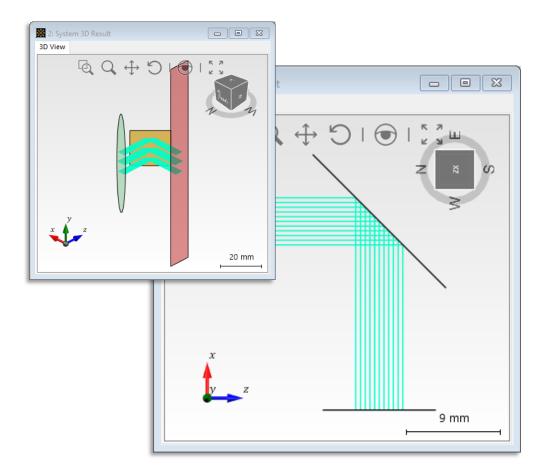
11 -	Surface	+/+ +/-	-//+	
	All Surfaces	+/+ +/-	-//+	
Coordinate	Surface #1 (Plane Surface)			
Systems	Surface #2 (Plane Surface)			
Position / Orientation Structure				
Channel Configuration				
Free Space				

## **Set Orientation & Run Ray Profile**

- In Position/Orientation, set Theta to 45°
- Click OK to apply all changes

Edit Lens System Co	omponent				×
21 -	Basal Positioning	Isolated Positioning	Position Information	on (Absolute)	
	- Position this Eler	ment's Input Axes with	n Respect to		
Coordinate	Reference Eleme	nt	0: Plane Wave	~	Enter Absolute
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ا 😓	-Relative Distance	e on Axis			
Position / Orientation	Delta Z		20 mm		
Orientation	Lateral Shift				
	Delta X	0 mm	De	Ita Y	0 mm
Structure	Inclination / Rot	ation			
	Orientat	ion Definition Type	Spherical Angles	~ (:::)	
1 m	8	Z-Axis Direction Def	inition		
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	1	Theta (Spherica	al) ~	45	
	Swap Order	Phi (Spherical)	~	0°	「
	(Criter)				

• Run the simulation in *Ray Profile, System: 3D*, to ensure the setup matches the expected configuration



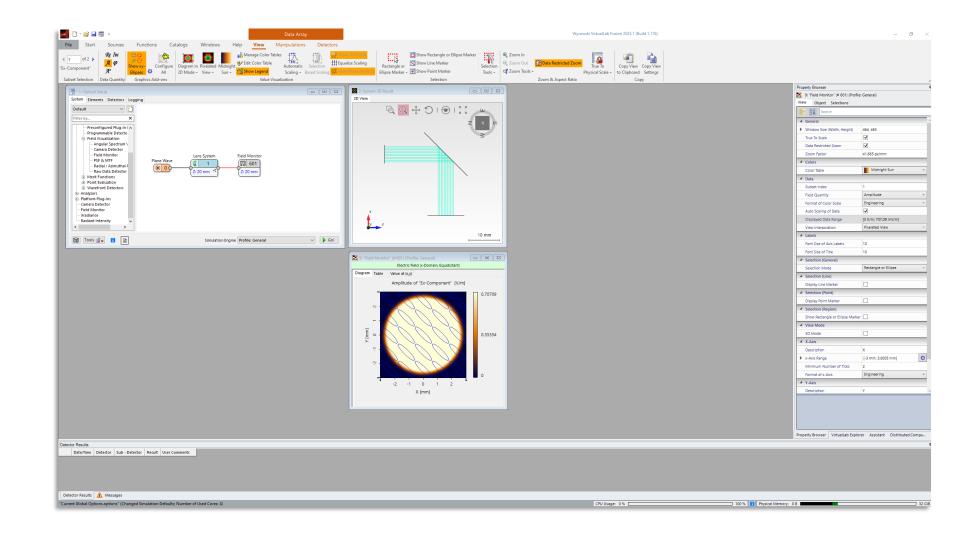
## **General Profile – Set up the Detector**

- Switch to General Profile
- Edit the Field Monitor
- Go to the Field Quantities tab
- Make sure Coherent Summation is selected
- Click the *cogwheel* ( on the cogwheel ( on th
- Check the box Show Polarization Ellipses
- Close all dialogs with OK
- Run the simulation

Edit Plug-In Detector (Fiel	d Monitor)								×			
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Detector	pply Paraxial Appro	oximation for Co	mponent	Calculatio	on?	Yes	⊖ No					
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### **General Profile – Set up the Detector**

Your screen should look like this:



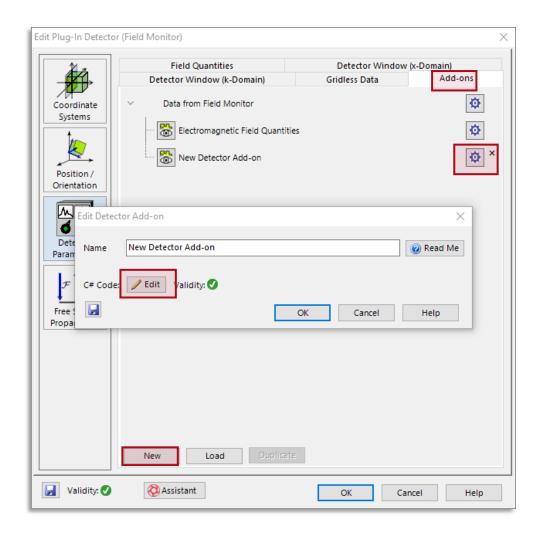
### **Create a new Detector Add-on**

*VirtualLab Fusion* provides the amplitudes and phases of *Ex* and *Ey* at the detector.

Our goal is to calculate the phase difference between them and adjust the setup parameters so that this difference becomes  $\pm 90^{\circ}$ .

For demonstration purposes, we will use the optimization routine, which requires a single-value merit function – in this case, the phase offset. To enable this, we'll program a simple *Detector Add-on* that outputs the required value:

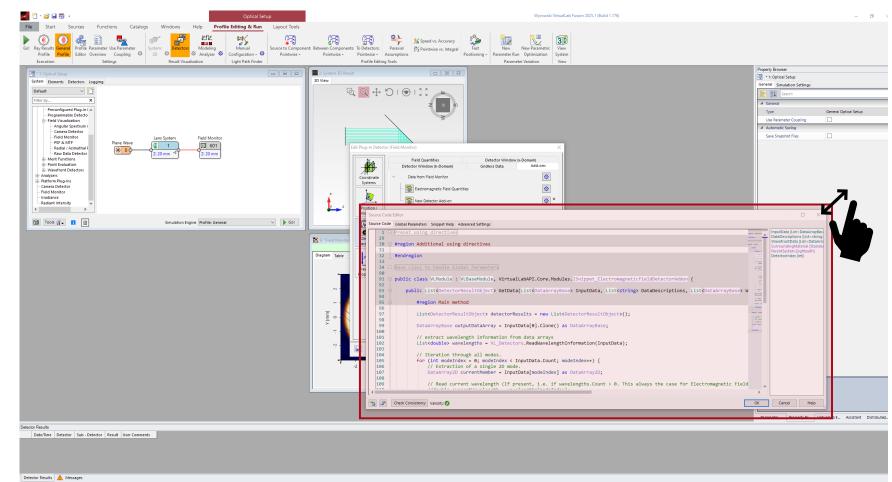
- Edit the Field Monitor
- Go to the *Add-ons* tab
- Click New
- Click the *cogwheel* icon
- Select *Edit* to open the C# code editor



## **Study the Snippet**

After clicking *Edit*, you'll see the code for a functional add-on. Before making any changes, let's review the key parts of the existing code relevant to our task.

Scale the Source Code Editor to a size that suits you.



# **Study the Snippet**

Line 99 and 102 are comments and do not affect the code.

Line 100 reads the wavelengths used in the simulation into a local list. Since we won't use wavelengths to calculate the phase offset, we will delete this line later, although leaving it doesn't cause any issues.

```
99 // extract wavelength information from data arrays
100 List<double> wavelengths = VL_Detectors.ReadWavelengthInformation(InputData);
101
102 // Iteration through all modes.
103 for (int modeIndex = 0; modeIndex < InputData.Count; modeIndex++) {</pre>
```

At line 103, the code starts looping through all modes. The loop code ends with the closing bracket at line 113.

113 }

Modes are different entries in the electromagnetic field data set. In this simulation:

- We use only one wavelength
- We have chosen to sum coherent modes, meaning we combine all possible light paths to the detector

Since this results in just one mode, we could remove the loop—but we'll keep it for clarity.

### **Study the Snippet – Part 2**

At line 105, the current mode's electromagnetic field is read into *currentMember*, a 2D array representing the detector's *x* and *y* dimensions. In this simulation, *currentMember* holds the complex values of *Ex* and *Ey*, the only components selected for this detector.

Edit Plug-In Detecto	r (Field Monitor)							×
21 -	Detector Window	v (k-Domain)		Gridl	ess Data		Add-ons	
	Field Quant	ities		De	etector Wi	ndow (x-D	)omain)	
Coordinate Systems	– Select Field Data Whi	ch Is Provideo	i to Detec	tor Add-C	ns			
Jystems		Ex	Ey	Ez	Hx	Hy	Hz	
	Components		$\checkmark$					
Position /	Domain	🗹 Sp	ace (x-Doi	main)	Fo	urier (k-Do	omain)	

104 // Extraction of a single 2D mode. 105 DataArray2D currentMember = InputData[modeIndex] as DataArray2D;

Line 117 generates a list of a value, its unit, and its name. Line 118 stores it in the output data of the detector.

This type of one-dimensional information will appear in the *Detector Results* window.

115		<pre>// sample detector output for physical values</pre>
116		List <physicalvalue> physicalValues = new List<physicalvalue>();</physicalvalue></physicalvalue>
117		<pre>physicalValues.Add(new PhysicalValue(1, PhysicalProperty.Length, "My Detector Result"));</pre>
118		<pre>detectorResults.Add(VL_Detectors.CreateDetectorResult(physicalValues));</pre>

### **Study the Snippet – Part 3**

Line 121 adds the contents of *outputDataArray* to the detector's output data. This two-dimensional information will be displayed in a result window.

120 121 // sample detector output for documents
detectorResults.Add(VL\_Detectors.CreateDetectorResult(outputDataArray, "My Detector Result"));

- Close the snippet by clicking *Cancel*, to ensure no changes are made to the code
- Close the *Edit Field Monitor* dialogue with *OK*, to activate *New Detector Add-on*
- Run the simulation

The *Detector Results* window will display the name of the add-on along with the information defined in line 117 of the snippet. Tip: You can find *Detector Results* next to the *Messages* tab at the bottom of the GUI.

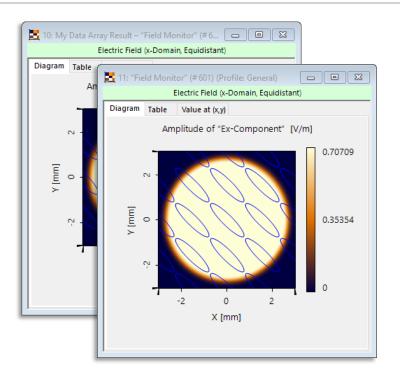
De	tector Results				
	Date/Time	Detector	Sub - Detector	Result	User Comments
1	2025-07-16 10:11:18	"Field Monitor" (# 601): New Detector Add-on (Profile: General)	My Physical Value Result	1 m	

Two result windows will appear:

one named Field Monitor

and the other My Data Array Result

The latter appears as a consequence of line 121 in the code of the new add-on. Line 97 clarifies why both windows display identical data, considering the snippet contains no code that modifies the output.



97 DataArrayBase outputDataArray = InputData[0].Clone() as DataArrayBase;

## **Update the Snippet**

#region Main method	#region Main method
<pre>ist<detectorresultobject> detectorResults = new List<detectorresultobject>(); DataArrayBase outputDataArray = InputData[0].Clone() as DataArrayBase;</detectorresultobject></detectorresultobject></pre>	<pre>List<detectorresultobject> detectorResults = new List<detectorresultobject>(); DataArrayBase outputDataArray = InputData[0].Clone() as DataArrayBase;</detectorresultobject></detectorresultobject></pre>
<pre>// extract wavelength information from data arrays List<double> wavelengths = VL_Detectors.ReadWavelengthInformation(InputData); // Iteration through all modes. for (int modeIndex = 0; modeIndex &lt; InputData.Count; modeIndex++) { // Extraction of a single 2D mode. DataArray2D currentMember = InputData[modeIndex] as DataArray2D;</double></pre>	<pre>// declare and initialize local variables double phase_x = 0; double phase_y = 0; double phase = 0; // Iteration through all modes. for (int modeIndex = 0; modeIndex &lt; InputData.Count; modeIndex++) {</pre>
<pre>// Read current wavelength (If present, i.e. if wavelengths.Count &gt; 0. This //double currentWavelength = wavelengths[modeIndex]; /************************************</pre>	<pre>DataArray2D currentMember = InputData[modeIndex] as DataArray2D; phase_x = currentMember.Data[0][256, 256].Arg(); // phase of Ex[256, 256] phase_y = currentMember.Data[1][256, 256].Arg(); // phase of Ey[256, 256] phase = phase_x - phase_y; // the phase difference while (phase &gt; Math.PI) // This block ensures phase -= 2 * Math.PI; // the phase difference while (phase &lt; -Math.PI) // is within phase += 2 * Math.PI; // the range -π to π</pre>
List <physicalvalue> physicalValues = new List<physicalvalue>(); physicalValues.Add(new PhysicalValue(1, PhysicalProperty.Length, "My Detector Re detectorResults.Add(VL_Detectors.CreateDetectorResult(physicalValues)); // sample detector output for documents detectorResults.Add(VL_Detectors.CreateDetectorResult(outputDataArray, "My Detector return detectorResults;</physicalvalue></physicalvalue>	<pre>} // sample detector output for physical values List<physicalvalue> physicalValues = new List<physicalvalue>(); physicalValues.Add(new PhysicalValue(phase, PhysicalProperty.AngleDeg, "Offset detectorResults.Add(VL_Detectors.CreateDetectorResult(physicalValues)); return detectorResults;</physicalvalue></physicalvalue></pre>
#endregion	#endregion

## **Finish Editing and Go!**

- Make all modifications to the snippet
- At the bottom-left corner of the Source Code Editor, click Check Consistency to find syntax errors (e.g. missing semicolons)
- Click OK, then rename the add-on to Phase Offset Add-on
- Click *OK* twice to save and close all dialogs
- Clear the *Detector Results* window (Tip: Right-click)
- Run the simulation.
- Inspect the Detector Results window

De	tector Results				
	Date/Time	Detector	Sub - Detector	Result	User Comments
1	2025-07-16 10:28:38	"Field Monitor" (# 601): Phae Offset Add-on (Profile: General)	Offset	-154.65°	

## **Finish Editing and Go!**

#### **Summary of Modifications:**

- Delete reading wavelength information
- Declare new variables for storing the phases of *Ex*, *Ey* and the phase offset
- Inside the mode-loop, remove the green comments and replace them with the code shown in lines 109 to 116.

- Use indices [256, 256] since these fall within the flat part of the plane wave
- In line 122 (*PhysicalValues.Add*) replace:
  - o 1 with phase
  - Length with AngleDeg
  - My Detector Result with Offset
- Delete the code responsible for the result window

# **Assess Diffraction and the Paraxial Approximation**

#### Diffraction

In this setup, diffraction will occur due to the finite size of the plane wave.

However, in this tutorial, we aim to focus solely on the physics of the *QWP* mirror, independent of the beam size. If possible, we would like to work under ideal conditions where the plane wave, mirror, and detector are all considered infinite in size.

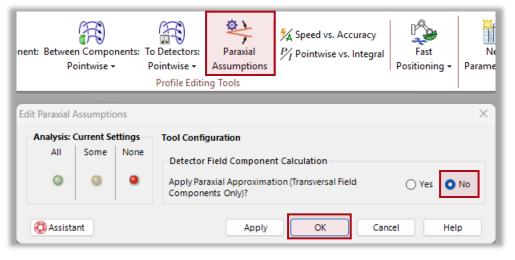
In the software we can achieve this by using pointwise propagation throughout the optical setup, effectively eliminating diffraction effects. (As a bonus, this also speeds up the simulations.)



#### **Paraxial Approximation**

The paraxial approximation sets *Ez* to zero and is valid from the source to the mirror and from the mirror to the detector. However, inside the coating, the plane wave's direction is not parallel to the mirror's axis, so the paraxial approximation should be disabled.

(Even though in the current simulation this has no effect on the results.)



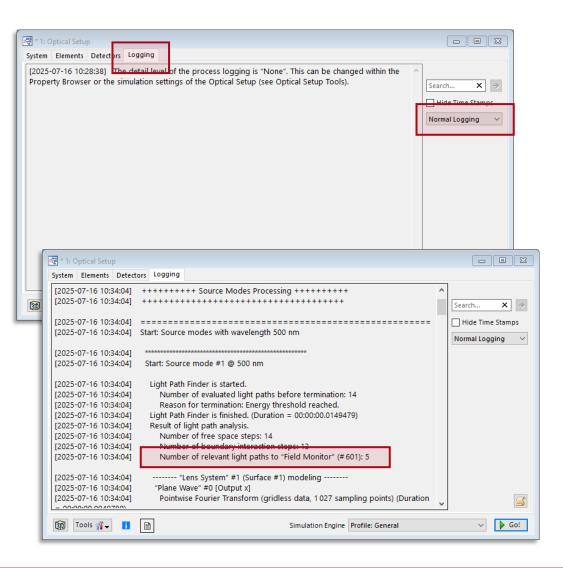
### **Evaluate Speed vs. Accuracy**

In *Educational Tutorial: Fabry-Pérot Interferometer,* we already explored the concepts of convergence and precision.

While the coated mirror theoretically supports an infinite number of interfering paths, only a limited few contribute significantly to the result.

- Go to the *Logging* tab in the *Optical Setup Editor*
- select Normal Logging
- Click Go! to run the simulation
- Scroll to the top of the logging data
- · Locate and review the following text

In *VLF*, simulations begin with the *Light Path Finder* routine, which runs partial simulations to identify possible light paths and estimate the energy they carry. Based on a predefined energy threshold, it has identified 5 relevant paths.



### **Evaluate Speed vs. Accuracy – Part 2**

- Click the *cogwheel* icon in the *Light Path Finder*
- Note the default *Energy Threshold* (0.01%)
- Set it to 1e-04%, click OK
- Run the simulation and inspect the log output
- Repeat with *Energy Thresholds*: 1e-06%, 1e-08% and 1e-10%
- Observe that the number of paths increases
- Review the *Detector Results* (new entries appear at the top)
- Set *Energy Threshold* back to 0.01%

	Help	Profi	e Editing & F	lun	Layout Tool	s	
ctors Visua			Manual Configuration Light Path Fir	<b>.</b> Ader	Source to Com Pointwise		Betw
Edit	Light Path I	Finder Co	nfiguration				X
	Energy Thre Maximum L Channel Res	Manual shold evel solution A	Channel Configu	ration	·	0.01 % 100 ‡ 1	
(	🔁 Assistant		ОК		Cancel	Help	

Based on the convergence, the default *Energy Threshold* of 0.01% appears sufficient to achieve ~  $0.5^{\circ}$  accuracy for the current setup and will therefore be used moving forward.

De	tector Results				
	Date/Time	Detector	Sub - Detector	Result	User Comments
5	2025-07-16 10:41:48	"Field Monitor" (# 601): Phae Offset Add-on (Profile: General)	Offset	-155.0928919°	
4	2025-07-16 10:41:07	"Field Monitor" (# 601): Phae Offset Add-on (Profile: General)	Offset	-155.0929095°	
3	2025-07-16 10:40:51	"Field Monitor" (# 601): Phae Offset Add-on (Profile: General)	Offset	-155.0905782°	
2	2025-07-16 10:40:27	"Field Monitor" (# 601): Phae Offset Add-on (Profile: General)	Offset	-155.1006471°	
1	2025-07-16 10:39:59	"Field Monitor" (# 601): Phae Offset Add-on (Profile: General)	Offset	-155.0777794°	

## Attempt to Create a QWP Mirror at 45°

Let us vary the coating thickness to determine if we can create a QWP mirror at 45°

- Start a new Parameter Run
- Vary *Distance* of *Surface* #2 from 0 to 200nm in steps of 5nm.

• Execute the Parameter Run

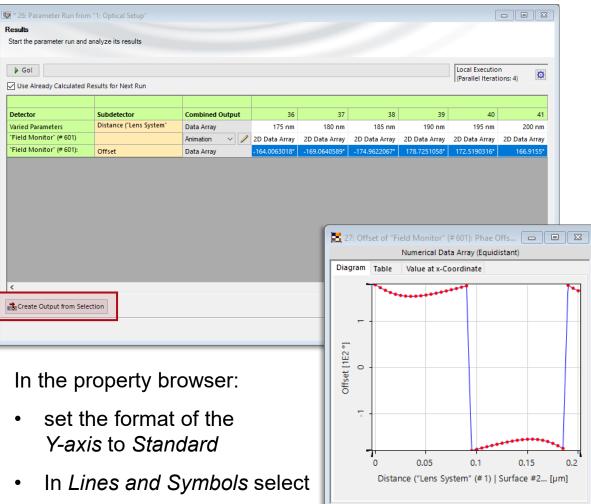
arameter Specifica	ation											
Set up the parameter		l.										
You can select one o	r more parame	ters which shall	I be varied as w	ell as the i	resulting n	umbe	er of iterat	ions. Sev	eral mod	es are ava	ilable	
specifying how the p												
Usage Mode Stan	daed	~										
Usage Mode Stan	dard	~										
dist								×	Show O	nly Varied	d Parame	te
1 2 * Paramet	ter Vary	From	То	Steps	Step Siz	e	Original \	/alue				
😑 "Lens System" (#	± 4)											
🗁 🖻 Basal Positio												
Distance Be		-1e+297 km	1e+297 km	1	2e+297	km		20 mm				
Surface #2 (P	lane Surface)	0 mm	200	41			4	50				
Distance		0 mm	200 nm	41	51	nm		50 nm				
Basal Position												
Distance Be		-1e+297 km	1e+297 km	1	2e+297	km		20 mm				
								< Back	) Ne	ext >	Sho	
								- Duck	JL	AC P		
💈 * 26: Parameter R	un from "1: On	stical Satura"										5
	un nom 1. op	lical setup										
Results Start the parameter i		ite cooulte										
Jan the parameter i	un anu analyze	na resulta										
Go!										xecution I Iteration	ns: 4)	
Use Already Calc	ulated Results f	for Next Run										
	Subdetector		Combined O	utput	1	2	3	4	5	6	7	
Detector												
Detector Varied Parameters	Distance ("Lei	ns System"	Data Array		0 mm 5	i nm	10 nm	15 nm	20 nm	25 nm	30 nm	

## Attempt to Create a QWP Mirror at 45°

- Select the Data Array holding Offset
- Click Create Output from Selection

#### Conclusion

It appears that a quarter-wave plate (QWP) mirror at 45° cannot be realized with a single-layer coating, as the phase offset never reaches ±90° for any thickness. (Note that ±180° corresponds to a trivial reflection, simply producing the mirror image of the polarization.)

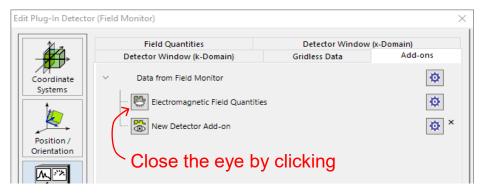


### **2D Parameter Run**

Our goal is to explore the combinations of *Theta* and *Distance* that lead to circular polarization.

- Disable storing plots of the field detector to avoid excessive memory usage
- Open a new *Parameter Run* document
- Let *Theta* run from 10° to 80° in 8 *Steps*

- Let *Distance* run from 0 to 200 nm in 26 *Steps*
- Set Usage Mode to Scanning to cover all  $8 \times 26$  combinations
- Note Number of Iterations: 208
- Execute the Parameter Run



1	2 *	Parameter		Mana	From	T-	Change	Chan Cine	Onining 1 Malus	
-	~			Vary	From	То	Steps	Step Size	Original Value	
		is System" (# 4)								
	θВ	asal Positioning (R Spherical Angle T		121	10	° 80°	8	10°	45°	
	"He	iversal Detector" (#			10	00	0	10	43	
		asal Positioning (R								
		Spherical Angle Th			-1e+300	° 1e+300°	1	2e+300°	0°	
sa	ge N	lode Scanning		~		Number of I	erations:			
_	_			~				208	w Only Varied Para	meter
di	_		Vary	∠ F				208		meter
di 1	st 2 *	lode Scanning		✓ F	[	Number of I		208 × Shor	w Only Varied Para	meter
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di:	st <sup>~</sup> Ler	lode Scanning Parameter Is System" (# 4) asal Positioning (F	Vary Relative)		rom	Number of I	Steps	208 X Sho Step Size	w Only Varied Para	

## **2D Parameter Run - Visualization**

- Select the data array containing *Offset*
- Click the pencil icon
- Select Separate Varied Parameters along 2 Dimensions
- Set Distance as the Abscissa
- Click OK
- Click Create Output from Selection

In the *Property Browser*.

- Set Format of Y-axis to Standard
- Deselect Auto Scaling of Data
- Set *Displayed Data Range* to [-180°; 180°]
- Set Format of Color Scale to Standard

< Back Next > We want to clearly visualize the ±90° offsets. To do this, we will adjust the color table so that the plot changes color precisely at ±90°.

Results

Go!

Detector

Varied Parameters

"Universal Detector

"Universal Detector" (# 600..

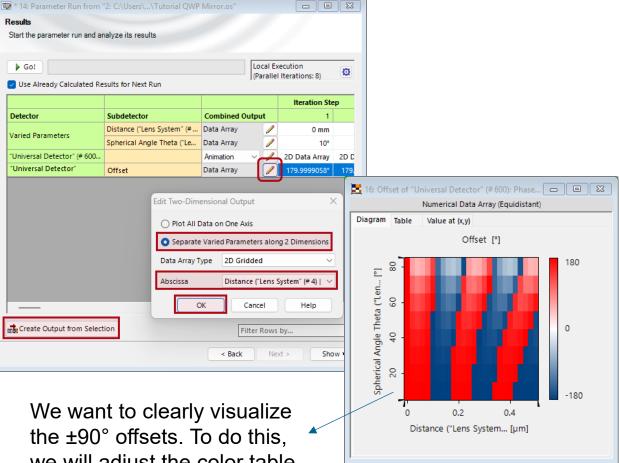
Create Output from Selection

Start the parameter run and analyze its results

Use Already Calculated Results for Next Run

Subdetector

Offset

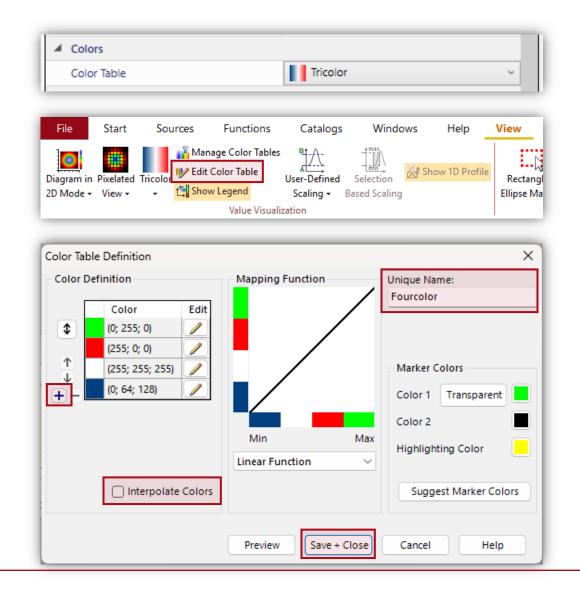


## 2D Parameter Run – Edit Color Table

- In the *Property Browser*, ensure *the Color Table* is set to *Tricolor*.
- In the View Ribbon, click Edit Color Table
- Click + and add an additional color (e.g., green)
- Deselect Interpolate Colors
- Assign a *Unique Name* to the new color table
- Click Save & Close

The result:

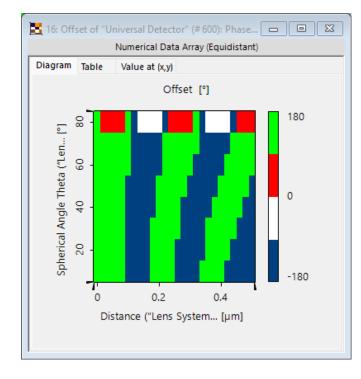
- Values from 0 to 25% of the range will appear blue
- 25% to 50% will be white
- and so on



### **2D Parameter Run – Select Color Table**

In the *Property Browser*, select the newly created *Color Table*

Colors		
Color Table	Fourcolor	~



At or near the red-green boundaries, the phase offset is expected to be +90°, while at or near the blue-white boundaries, it should be  $-90^{\circ}$ .

The green-blue transitions indicate  $2\pi$  phase jumps, which have no physical meaning due to the periodic nature of phase.

The plot suggests that solutions occur at relatively large angles of incidence. To investigate this further, we will increase the resolution by refining the step sizes for *Theta* and *Distance*, while limiting the *Distance* range to 0-200 nm and the *Theta* range to  $60-80^{\circ}$ .

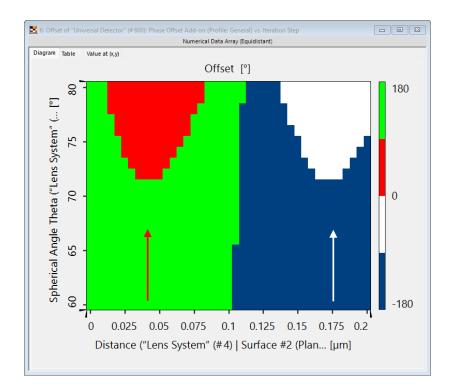
### **2D Parameter Run – Refine**

- At the bottom of the *Parameter Run* document, click *Back* a few times, to return to the *Parameter Specification* window
- Vary *Theta* from 60° to 80° with Step Size 1°
- Vary *Distance* from 0 to 200 nm in steps of 5 nm
- Execute the Parameter Run
- Plot the result and format as before

The smallest angles of incidence appear to occur at  $\sim$  42.5 nm for a phase offset of +90° and at  $\sim$  172.5 nm for a phase offset of -90°, as indicated by the arrows.

In the next step, we will use the *Parametric Optimization* tool to find *Theta* for both of these coating thicknesses.





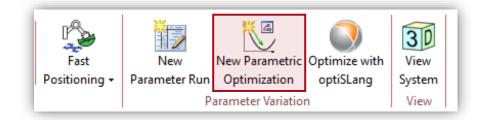
Tip: Use the *Point Marker* under *Selections* in the *Property Browser* to locate coordinates and read values on the plot.

### **Parametric Optimization**

• Make the coating 42.5 nm thick

_	_	_			
Index	Distance	Position	Туре	Homogeneous Medium	Comment
1	0 mm	0 mm	Plane Surface	n = 1.5	Enter your cor
2	42.5 nm	42.5 nm	Plane Surface	Air in Homogeneous M	Enter your cor

• Start a *Parametric Optimization* 



γοι	I can select one or more para	meter w	hich shall be varied	d within the optimization.
th	eta			
_				
1	2 * Parameter	Vary	Original Value	
Ξ	"Lens System" (# 4)			
4	Basal Positioning (Relativ	e)		
	Spherical Angle Theta		45°	•
			,	

• Select Theta to be varied

35

### **Parametric Optimization**

- Enter the *Target Value* for *Offset* (90°)
- Click Update

nsidered during optin	nization						
Constraint Name	Use	Weight	Constraint Type	Value 1	Value 2	Start Value	Contribution
Basal Positioning						45°	
Offset		1	Target Value	90			
	Constraint Name Basal Positioning	Constraint Name Use Basal Positioning	Basal Positioning	Constraint Name Use Weight Constraint Type Basal Positioning	Constraint Name Use Weight Constraint Type Value 1 Basal Positioning	Constraint Name Use Weight Constraint Type Value 1 Value 2 Basal Positioning	Constraint Name Use Weight Constraint Type Value 1 Value 2 Start Value Basal Positioning 45°

• Set *Maximum Tolerance* to 1e-05

Optimization Algorithm	Downhill Sim	plex ~
Maximal Number of Iterati	ons	500
Maximum Tolerance		1e-05
Initial Step Width Scale Fac	tor	1

High accuracy will not be necessary, since we have limited the number of paths using an *Energy Threshold* of 0.01%.

# **Parametric Optimization – Part 2**

Run the optimization •

otart or stop the optimization	on routine. The results are sho	wn in the table.						Diagram	1	umerical Data Array (Non-Eq Value at x-Coordinate
Go!								·······································		
Detector	Subdetector	Combined Output	>	21	22	23	24	4.	$\square$	
Optimizer Logging	Target Function Value	Data Array	5 3	2.704685351e-05	3.728985242e-06	7.98633961e-06	5.488127647e-07			
Parameter Constraints	Spherical Angle Theta	Data Array	•	71.2265625°	71.33203125°	71.26171875°	71.31445313°		1 1	
"Field Monitor" (# 601):	Offset	Data Array	•	90.29797581°	89.88935852°	90.16191852°	89.9575542°	2°]		
								Offset [1E2 1 1.2		
< میں Create Output from Sel							>	0.8		$\bigvee$

The routine used 24 steps for convergence

Select Show Optimized Optical Setup •

A copy of the Optical Setup will appear, with the only difference being that *Theta* now has the optimized value.

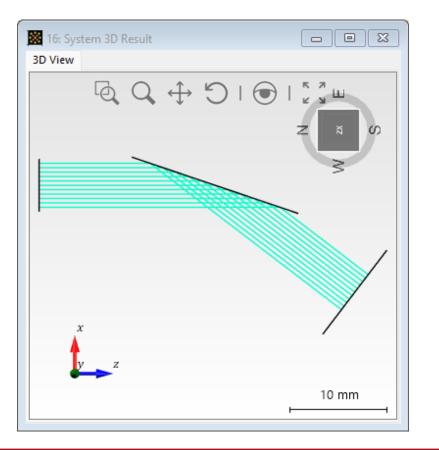
Filter Rows by	×
< Back Next >	Show <b>*</b>
	Show Initial Optical Setup
	Show Optical Setup for Certain Simulation Step
	Show Optimized Optical Setup

Phae Offs... 🗖 🗐 🔀

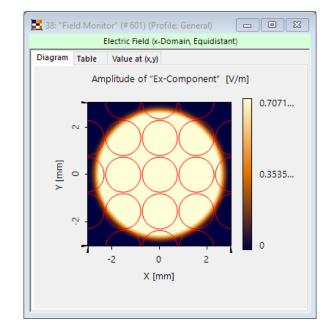
20

## **Optimized Optical Setup**

• In the optimized setup, generate a 3D plot in the *Ray Results Profile* 



- Enable the output of the *Electromagnetic Field Quantities* (open the eye)
- Run the simulation in the General Profile



Indeed, the polarization is circular. The optimized setup and the optimization document can now be closed without saving.

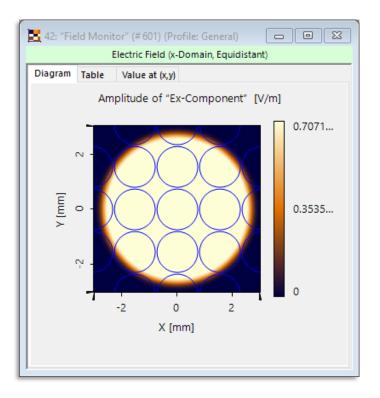
## **Parametric Optimization – Different Thickness**

-90

- Change the coating thickness to 172.5 nm
- Run a new *Parametric Optimization*, this time with an *Offset Target Value* set at -90°

Offset		1 Target Value
Simulatio	on Step	
22	23	24
851404e-06	1.094502828e-05	4.560954968e-08
1.33203125°	71.26171875°	71.31445313°
9. <b>92042585°</b>	-90.18955318°	-89.98776369°

- Create the Optimized Optical Setup
- Open the eye
- Run the simulation in the General Profile



Again, the polarization is circular, but now the circles are blue.

### **Polarization Ellipses Properties**

- Continue working with the optimized setup
- Open the properties of the *Polarization Ellipses*

The color indicates the direction of rotation of the *E*-field as seen by the detector (Tip: The detector acts as the observer, looking towards the incoming light).

13: "Universal Detector" (# 600) (Profile: Genera Electric Field (x-Domain, Equidist

Amplitude of "Ex-Component"

X [mm]

Diagram Table Value at (x,y)

- Set *Minimum Cell Size (Screen Pixels)* to 20
- Select Draw Arrows
- Close all dialogs by clicking OK
- Run the simulation

				indow (k-E Quantities	omain)			ess Data tector V	Vindow (x-E	Add-ons Domain)
	Coordinate	Selec	t Field Dat	a Which Is	Provided	to Deteo	tor Add-O	ns		
	Systems	Cor	nponents		Ex	Ey 🗹	Ez	Hx	Ну	Hz
	Position /	Dor	main		🗹 Spa	ace (x-Do	main)	F	ourier (k-Do	omain)
	Edit Electromagnetic Field	Quantity Vi	sualizatio	n Settings				×		¢
	Field Components & Do	main								
	Components	Ex	Ey	Ez	Hx	Ну	Hz		⊖ Yes	No
	components	$\checkmark$							Yes	⊖ No
	Domain	🗹 Spa	ce (x-Dom	ain)	Four	rier (k-Do	main)		mation	$\sim$
Edit Vie	ew Settings for Array of Pola	rization Elli	pses in xy	-Plane	×					
						efront Ph	ase)			
Line V	Nidth 10				ober	rical Part				
	Width 1.0				pher	rical Part				
Dire	Width 1.0				pher	rical Part	~	<u>19</u>		
	ection of Rotation				nold			<b>發</b> 1 %		
	ection of Rotation Draw Arrows Different Colors	Counterclo	ckwise Col	or 📕	nold					
	ection of Rotation Draw Arrows Different Colors ckwise Color	Counterclo	ckwise Col	or 📕						
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071 Clo 535	ection of Rotation Draw Arrows Different Colors ckwise Color	)	50		nold	1			Cancel	I Help
7071 Clo 1535 Min	ection of Rotation Draw Arrows Different Colors ckwise Color d imum Cell Size (Screen Pixels) raction via Neares		50	_	hold Sun	1	0.	1%	Cancel	I Help
7071 Clo 3535 Extr	ection of Rotation Draw Arrows Different Colors ckwise Color	)	50		hold Sun		0.	1%	Cancel	I Help

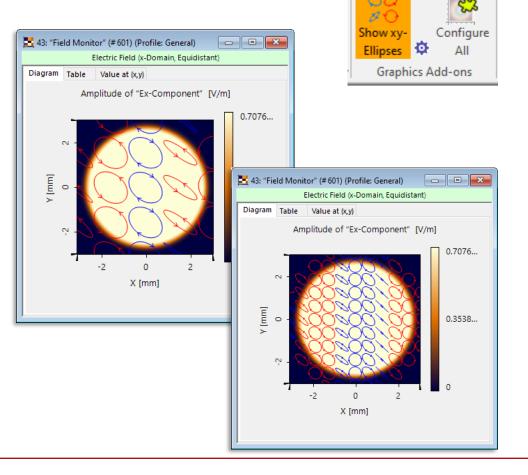
# **Ideas for Further Simulations – Wedge-Shaped Coating**

• Set *Alpha* of the first surface to 0.000988°.

This creates a wedge-shaped coating, with zero thickness at one end and a thickness of 172.5 nm at the center.

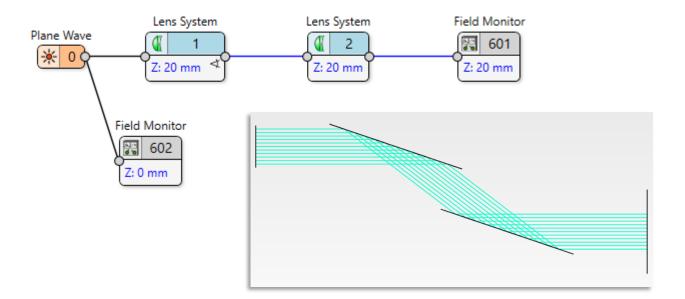
Coordinate Systems	:			_			
Position /		Index	Distance	Position	Туре	Homogeneous Medium	Comment
Orientation		1	0 mm	0 mm	Plane Surface	n = 1.5	Enter your co
		2	172.5 nm	172.5 nm	Plane Surface	Air in Homogeneous M	Enter your co
Structu	lit Plane S tructure		Discontin	uities Sca	ling Coating Period	ization	×
2							
	Orientati						_
	Orientati		na		0.000988°		
	Orientati Cartes	on			0.000988° 0°		
X	Orientati Cartes	on ian Alph ian Beta n Area	I	-			
Solve	Orientati Cartes Cartes Definitio	on ian Alph ian Beta n Area d Shape		- - Rectangula	0°		

- Run the simulation
- Configure the Ellipses

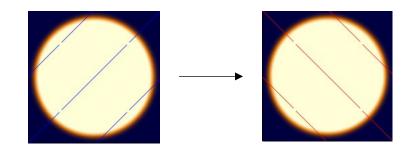


## **Ideas for Further Simulations – Two QWP Mirrors**

- Set Alpha of the first surface back to 0°
- Set the *Energy Threshold* to 1e-04%
- Copy the *Lens System* and edit the setup to create the following configuration



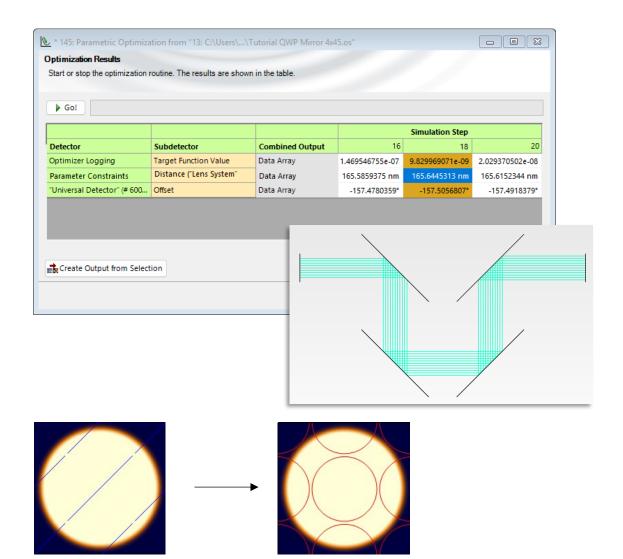
- Use coating thicknesses of 172.5 nm each
- Verify that the two mirrors together now function as a half-wave plate



# Ideas for Further Simulations – Four $\lambda/16$ Mirrors

- Use one mirror at 45°
- Notice that a reflection phase offset of –157.5° corresponds to a 22.5° shift, exactly one-sixteenth of a full wave (360°/16)
- Keep *Energy Threshold* = 1e-04%
- Use *Parametric Optimization* to find a coating thickness of app. 139.5 nm or 165.6 nm
- Continue with the Optimized Optical Setup
- Create a system of four  $\lambda/16$  mirrors

- Set the *Energy Threshold* to 1e-06%
- Verify the generation of circular polarization



## Conclusion

This second educational tutorial built upon the foundational skills introduced in the Fabry–Perot interferometer tutorial and guided you through more advanced features and applications of *VirtualLab Fusion (VLF)*.

#### You learned how to:

- Use *the Lens System* component to configure more complex optical setups,
- Program and apply a *Field Monitor Add-on* to extract customized simulation data,
- Conduct a 2D *Parameter Run* to explore the impact of multiple variables,
- Utilize VLF's Optimization tool to fine-tune system parameters, and
- Design a quarter-wave plate (*QWP*) mirror that converts linear to circular polarization—without the use of birefringent materials.

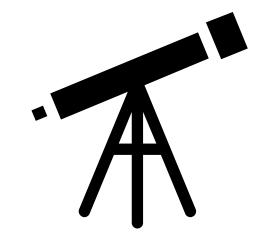


### Conclusion

In addition to gaining deeper proficiency with *VLF's* tools, you explored how simple thin-film-coated mirrors can replicate the function of waveplates under the right conditions.

This hands-on example demonstrates how *VLF* can be used not only for simulating optical systems, but also for visualizing and understanding complex physical phenomena. If you encountered challenges along the way, we encourage you to revisit the first tutorial to reinforce the basics.

You're now well-prepared to continue exploring more advanced simulations and custom designs in *VLF*.



title	Educational Tutorial: Quarter-Wave Plate Mirror
document code	TUT.0447
document version	1.0
required packages	_
software version	2025.1 (Build 1.176)
category	Tutorial
further reading	<ul> <li><u>Educational Tutorial: Fabry-Pérot Interferometer</u></li> <li><u>Ellipsometry Analyzer</u></li> </ul>