

#### **Educational Tutorial: Fabry-Pérot Interferometer**

This Educational Tutorial requires no prior knowledge of VirtualLab Fusion and can be completed using the trial version of the software within two hours.

#### **Short Abstract**



A Fabry-Pérot interferometer (FPI) is an optical device that utilizes multiple-beam interference to analyze light with exceptional precision. In its simplest form, it consists of two parallel, partially reflective mirrors, with a spacing that can be either fixed or adjustable over small distances.

In this tutorial, we will configure an idealized Fabry-Pérot interferometer consisting of two flat surfaces with mathematically defined reflectivities.

#### Introduction



Variable Distance between Mirrors

- A Fabry-Pérot interferometer (FPI) is an optical device that employs multiple-beam interference to analyze light with exceptional precision. In its simplest configuration, it consists of two parallel, partially reflective mirrors, with the spacing between them either fixed or adjustable over small distances.
- When light enters the cavity, it partially reflects back and forth between the mirrors, creating multiple light paths that interfere with each other. Only specific wavelengths experience constructive interference, producing sharp transmission peaks. Key features include:

- Free Spectral Range (FSR): The spacing between transmission peaks.
- Finesse: The sharpness of these peaks, representing the resolution
- FPIs are extensively used in spectroscopy, laser tuning, and optical communications due to their ability to scan and isolate specific wavelengths.
- In this tutorial, we will configure an idealized Fabry-Pérot interferometer composed of two flat surfaces with mathematically defined reflectivities. A plane wave will be used as the light source, and we will record the amount of light transmitted through the interferometer.
- We will use a fixed wavelength and observe the transmission as a function of the distance between the mirrors. This analysis will be carried out for three different reflectivities.

## **Simulation Workflow in this Tutorial**

- 1. Build the optical setup and perform a ray-tracing simulation. This quick simulation verifies the system's behavior and ensures that no obvious errors are present.
- 2. Evaluate electromagnetic fields using pointwise propagation, neglecting diffraction effects. This method remains computationally efficient.
- 3. Configure the detector to measure radiant flux, determining how much light passes through the interferometer. Normalize to power to simplify analysis.
- 4. Add partially reflecting coatings and enable nonsequential field propagation. The interferometer relies on the interference of multiple light paths.
- 5. Verify that the simulation converges and achieves acceptable precision. This ensures that results are reliable before proceeding further.

- 6. Evaluate whether diffraction must be included in the simulation to obtain accurate results. Prefer simulations without diffraction, as they are computationally faster.
- 7. Test the feasibility of using the paraxial approximation as another method to simplify and accelerate the simulation.
- 8. Lower the detector resolution to accelerate the simulation, reduce memory usage, and verify its validity.
- 9. Vary the length of the Fabry–Pérot Interferometer (FPI) to observe its effect on the transmission.
- 10. Simulate with increasing reflectivities. Higher reflectivity improves FPI resolution but also increases simulation time, as more light paths must be included.

## **Build a Setup**

- Start VirtualLab Fusion
- Select New > Optical Setup

- In the Optical Setup View filter by plane
- Drag and drop one *Plane Wave*
- Drag and drop two Ideal Plane Surfaces
- Undo the filter function by clicking on the cross
- From the bottom of the list drag and drop one *Field Monitor* into the setup





# **Position Elements, Perform Ray Tracing**

- Use the mouse to connect the elements
- Double click on the *Plane Wave* icon, select the tab *Spectral Parameters* and set the wavelength to 500 nm
- Click on the boxes below the other three elements and set the z values to 20, 10, and 20 mm. Tip: The position is with respect to the previous element

- Select Ray Results Profile and System: 3D
- Press Go!

- Locate the black cube in the result window
- Click on the zy plane to change the perspective







## **Result windows**

- Verify the result window now looks like this
- Try out the tools at the top
- Right click on the result window and investigate the available tools
- Using the mouse, toggle between the result window and the setup window. Observe how the ribbon at the top adjusts based on the selected window. Tip: Keep this feature in mind if you cannot find a specific function
- Select the General Profile
- Note that all propagation is *Pointwise*
- Press Go!

Execution Settings Layout Tools Source to Component: Between Components: To Detectors: Pointwise - Pointwise -

Profile Parameter Use Parameter

Coupling

Editor Overview

Go!

Ray Results General

Profile

Profile





- Observe that the Ex-component is normalized to 1 V/m
- Observe the soft edge of the plane wave, reducing diffraction effects.
- Investigate the tabs Table and Value at (x,y)

#### **Result VLF Screen**

Your screen should now look like this:



# **Activate the Radiant Flux Detector Add-On**

• Open the *Profile Editor* 



- Select Visualization & Detectors
- Select Detector Settings
- Select Add-ons
- Select Load
- From *Radiometry*, select *Radiant Flux & Efficiency* (*Surface*) and press *OK*
- Use the slide bar on the right to scroll down
- Click on the cog wheel

- Click on Read Me
- Verify that the Add-on requires all six components of the electromagnetic field in the x-domain as input







## Normalize the Source Power, Set the Air Pressure

- Switch to the tab Field Quantities
- Observe that the x-domain is selected
- Tick all six field components

Field Quantities	Detector	Window (x-Domain)	Detector Windo	w (k-Domain)	Gridless	Data A	dd-ons			
Filter Controls b	y		×						III	Ξ
Name		Settings								
"Universal Detector" (# 600	))	Sele	ect Field Data Whi	ich Is Provided	to Detec	tor Add-O	ns			
			omnonents	Ex	Ey	Ez	Hx	Hy	Hz	
			omponents							
		D	omain	🖉 Spa	ice (x-Dor	main)	- Fo	urier (k-Do	omain)	

- Switch to Sources
- Select the tab Power Management
- Tick the box Activate Power Management
- Set the Power to  $100 \ \mu W$
- On keyboards without µ simply type uW
- Tip: In *Parameter Overview* it is possible to edit the *Relative Edge Width* of the *Plane Wave* source
- Switch to Other Settings
- For demonstration purposes, set the air pressure to zero such that the wavelength equals the vacuum wavelength of 500 nm. Alternatively select Vacuum as the Homogenous Medium behind every element
- Close the *Profile Editor* by pressing *OK*

P	rofile Editor (Mo	deling Profile: General)		
	) Sources	Parameter Overview Position Spectral Parameters Type of Power Spectrum	& Size Power Management <ul> <li>Discrete</li> </ul>	Continuous
	C.A.	-Source Power Management	ent Source Modeling Power	100 μW

Visualization & Detectors	Environment	
	Air Pressure	0 Pa
Other Settings	System Temperature	20 °C
ould betailigs		

# **Add Coatings**

- In the General Profile, click Go!
- Locate the *Detector Results* window (normally at the bottom of the VLF master window, together with the *Messages* window)
- Verify that the *Radiant Flux* equals 100 μW
- Double-click on the icon of the first *Ideal Plane Surface*
- Click on the load icon in the coating panel
- From Functional Coatings, select Perfect Reflection
- Press OK
- Click on the edit icon in the coating panel
- Set the *Reflectance* to 0.04 (uncoated glass), press *OK*
- Add the same coating to the second *Ideal Plane Surface*

		Detector Results				
		Date/Time	Detector Sub - Detector	Result		
		Messages Deter	tor Results			
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	Date/Time		Detector		Sub - Detector	Result
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		<b></b>		9	×	
				Variable Paramete	er	
		Reflectance		0.04 🕑		
		Transmitta	nce	0.96		

# Set the Light Path, Check the Convergence

- In the General Profile, click Go!
- Verify that the *Radiant Flux* equals 92.16 μW
- Open the *Profile Editor*, select *Other Settings* and *Light Path Finder*
- Observe that the Channel Configuration is set to Pre-Selected
- In Components & Solvers, select Channel Configuration
- Observe that only the +/+ channels (forward transmission) are selected
- In the Light Path Finder switch to Manual
- Edit the *Channel Configuration* and enable the modeling of light bouncing between the two surfaces. Press *OK*
- Run the simulation and observe the *Radiant Flux*
- Open again the *Light Path Finder* and set the *Energy Threshold* to 0.0001%
- Repeat the simulation and observe the Radiant Flux

198	System Free Space F	Propagation Light Path F	Finder	
Settings	Channel Configurat	ion Option	Pre-Selected	~
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Energy Threshold

0.0001 %

# **Verify Pointwise vs. Integral and Paraxial Assumptions**

🔣 Speed vs. Accuracy Select Pointwise vs. Integral Source to Component: Between Components: To Detectors: Paraxial P/I Pointwise vs. Integral Fast Pointwise -Pointwise -Pointwise + Assumptions Positioning • **Profile Editing Tools** Change to *All Automatic*, enabling diffraction Profile Editing Tool: Pointwise vs. Integral  $\times$ Run the simulation Selection Mode Compare the *Radiant Flux* with the previous value All Pointwise All Integral Individual All Automatic 5 Speed vs. Accuracy Select Paraxial Assumptions Source to Component: Between Components: To Detectors: P/I Pointwise vs. Integral Paraxial Fast Automatic -Automatic 🕶 Automatic -Assumptions Positioning -**Profile Editing Tools** Switch off the *Paraxial Approximation* by selecting *No* Detector Field Component Calculation Run the simulation Apply Paraxial Approximation (Transversal Field 🔿 Yes 🚺 🖸 No Compare the *Radiant Flux* with the previous value Components Only)? Switch the *Paraxial Approximation* back on again Profile Editing Tool: Pointwise vs. Integral Set *Pointwise vs. Integral* to *All Pointwise* to switch Yes O No Selection Mode diffraction off Individual All Pointwise

## Lower Detector Resolution, Reduce Memory Usage

• Double click on the icon of the Field Monitor

- Under *Detector Parameters*, select the *Detector Window (x-Domain)* tab
- Set the number of Grid Points to the lowest value
- Click OK and run the simulation
- Compare the *Radiant Flux* with the previous value to verify the validity of using a lower resolution
- Tip: The *Edit Field Monitor* window appears differently when the *Ray Results Profile* is active



Plug-In Detecto	r (Field Monitor)	
	Detector Window (k-Domain)         Gridless Data         Add-ons           Field Quantities         Detector Window (x-Domain)	
Coordinate Systems	Detector Window Centered Around O Detector Position O Center of Field Mode	
×.	Lateral Window Position 0 mm × 0 mm Detector Window Size	
Position / Drientation	From Field Data (Per Mode)     O Manual Setting (All Modes)	
Detector	Size Scaling Factor	
Parameters	O From Field Data (Per Mode)   Manual Setting (All Modes)	
$\mathcal{F} \mathcal{F}^{-1}$ Free Space	<ul> <li>○ Set Grid Period</li> <li>● Set Grid Points</li> <li>Grid Points</li> <li>128<sup>2</sup> (1:1)</li> <li>128<sup>2</sup> × 128<sup>4</sup></li> </ul>	

# Vary the Distance Between the Mirrors

- Clean up the work space by clicking *Close All Result Windows* in the Windows ribbon
- To clean up the *Detector Results* window, right-click on it and select *Clear Detector Results* from the menu
- Save your Optical System before starting the next step.
- Ensure that the General Profile is active
- Select New Parameter Run
- Click Next
- In the filter function start typing distance
- Observe that *dis* suffices
- Locate the value 10 mm
- The corresponding parameter will be varied
- Tick the appropriate checkbox
- Enter From 9.999 mm, To 10.001 mm and Steps 201
- Observe that Step Size automatically updates to 10 nm



## Vary the Distance Between the Mirrors

- Clean up the work space by clicking *Close All Result Windows* in the Windows ribbon
- To clean up the *Detector Results* window, right-click on it and select *Clear Detector Results* from the menu
- Save your Optical System before starting the next step.
- Under Global Options / File Handling you can additionally choose:
  - "Automatic Saving" good for Parameter Runs and Parametric Optimization.
  - "Save Snapshot Files for optical Setups"

Tip: Only documents which have already been saved will be saved automatically.



### **Execute the Parameter Run**

- Click Next three times
- Press Go!
- Let the simulation finish
- Click on Radiant Flux to select the row
- Click on Create Output from Selection
- With the *Result Window* selected, find the *Property Browser.*
- Tip: The *Property Browser* and the *Assistant* window are usually separate tabs within the same window located on the right side of the VLF Master window
- Locate the properties of the Y-Axis
- Uncheck the Auto Scaling of Data

Go! Use Already Calculated Results for Next Run			Local (Parall	Local Execution (Parallel Iterations: 8)				
			Iteration Step					
Detector	Subdetector	Combined Output	1	2	3	4	5	6
Varied Parameters	Distance Before ("Ideal Pla	Data Array	9.999 mm	9.999 mm	9.999 mm	9.999 mm	9.999 mm	9.9991 mm

			Iteration Step			
Detector	Subdetector	Combined Output	144	145	146	
Varied Parameters	Distance Before ("Ideal	Data Array	10 mm	10 mm	10 mm	
"Universal Detector" (# 600		Animation 🗸 🥖	2D Data Array	2D Data Array	2D Data Array	2D Dat
"Universal Detector" (# 600	Radiant Flux (Surface)	Data Array	90.65 μW	92.479 μW	94.351 μW	96.1

Create Output from Selection			
Property Browser		д	
🛃 43: Radiant Flux (Surface) of "Universal Dete	ector" (# 600): R	adiant Flux Efficiency (Surface) (	
View Object Selections			
Search			
▲ General			
Transposed View			
Window Size (Width Height)	400 420	Y-Axis	
,	,	Read Labels from Inside	$\checkmark$
		Logarithmic Scaling	
		Minimum Number of y-Axis Ticks	2
		Format	Engineering v
		Is Description User-Defined	
		Description	Radiant Flux (Surface)
		Auto Scaling of Data	
		Data Range	[84.944 µW; 99.666 µW]

## **Optimize the Visualization of the Data**

- Set the Data Range from 0 to 100 μW
- Tip: The X-Axis Description can be changed in its properties settings
- Click on the icon of the first *Ideal Plane Surface*
- Click Edit Coating
- Set the *Reflectance* to 0.5
- Do it for both Surfaces
- Run the simulation and observe the Radiant Flux
- In Light Path Finder set Energy Threshold to 1e-6 %
- Repeat the simulation and observe the Radiant Flux
- Start a New Parameter Run
- From 9.999875 mm, To 10.000375 μm, Step Size 25 nm
- Execute the *Parameter Run* and generate a plot
- Ensure under *File/Global Options* that the *Number of Significant Digits* equals at least 10





# **Visualization: Adjust the Interpolation**

- Set the *Y-Axis Data Range* from 0 to 100 µW
- Under the Manipulations ribbon, select Coordinate and Interpolations Settings, and switch to Cubic 8 Point
- In the *Property Browser*, set *Minimum Number of Ticks* to e.g. 4





- Set the *Reflectance* to 0.95 for both Surfaces
- Run the simulation and observe the Radiant Flux
- In *Light Path Finder* set *Energy Threshold* to 1e-8 % and set the *Maximum Level* to 300
- Repeat the simulation and observe the *Radiant Flux*



# **Final Simulation**

- Warning: The following parameter run may last several minutes. For a quicker but inaccurate simulation limit the number of light paths by setting the *Maximum Level* to 50. The effect is still visible
- Execute a New Parameter Run from 9.999875 mm to 10.000375 mm with Step Size 25 nm and generate a plot
- Observe the values around the peak at 10 mm
- Ensure the box *Use Already*... is checked
- Click *Back* several times and change the *Step Size* to 5 nm
- Click Next several times and press Go!
- Generate plot
- In the *View* tab, try out *No Interpolation* and *Pixelated Interpolation*
- Reselect Interpolated View
- Under *Manipulations* try out different *Interpolation* Settings

▶ Go! ✓ Use Already Calculated Research Calculated Rese	esults for Next Run			Local Execu (Parallel Iter	tion rations: 8)
				Iteration Step	
Detector	Subdetector	Combined Output	5	6	7
Varied Parameters	Distance Before ("Ideal	Data Array	9.999975 mm	10 mm	10.000025 mm
"Universal Detector" (# 600		Animation 🗸 🥒	2D Data Array	2D Data Array	2D Data Array
"Universal Detector" (# 600	Radiant Flux (Surface)	Data Array	683.6185458 nW	99.90885725 µW	683.6185451 nW
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Create Output from Selec	tion			Filter Rows by.	
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## **Ideas for Further Simulations**

- For a fixed distance between the two mirrors, vary the wavelength of the source
- Repeat for a different distance and compare the results
- Tip: Always start with fast and inaccurate calculations and increase the accuracy once parameters are as desired

- Investigate the effect of misalignment
- Tilt the second mirror by e.g. 0.05°





# **Summary of Skills Acquired**

#### Congratulations on completing this educational tutorial

Throughout this tutorial, you have acquired a range of valuable skills, including:

- Setting up an optical system
- Adding sources, components, and detectors
- Positioning elements and generating 3D views
- Switching between rays and electromagnetic fields
- Using a Detector Add-on and normalizing to power instead of amplitude
- Adding functional coatings and setting up the light path
- Utilizing Energy Threshold and Maximum Level for convergence testing
- Toggling between pointwise and integral Fourier transforms
- Enabling and disabling the Paraxial Approximation,
- Changing the detector resolution
- Executing a Parameter Run
- Adjusting the range of coordinate axes in plots
- Editing interpolation settings

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