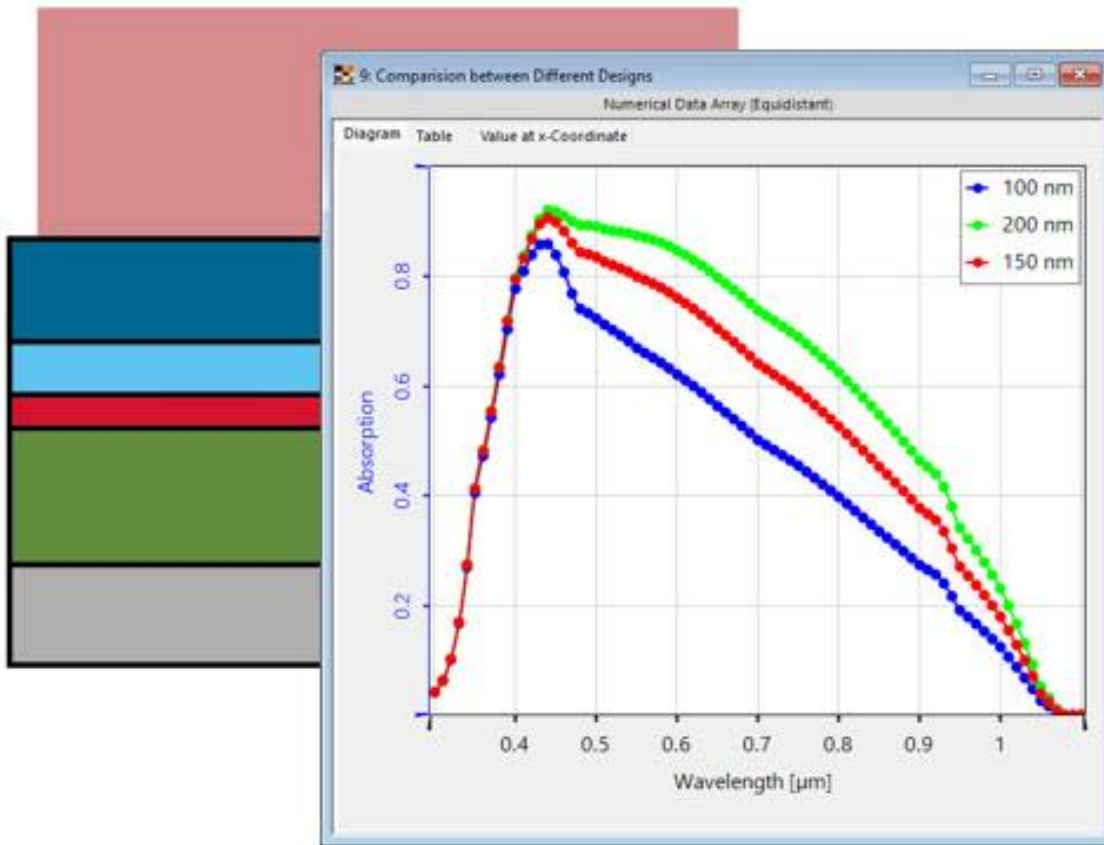


# Absorption in a CIGS Solar Cell

# Abstract



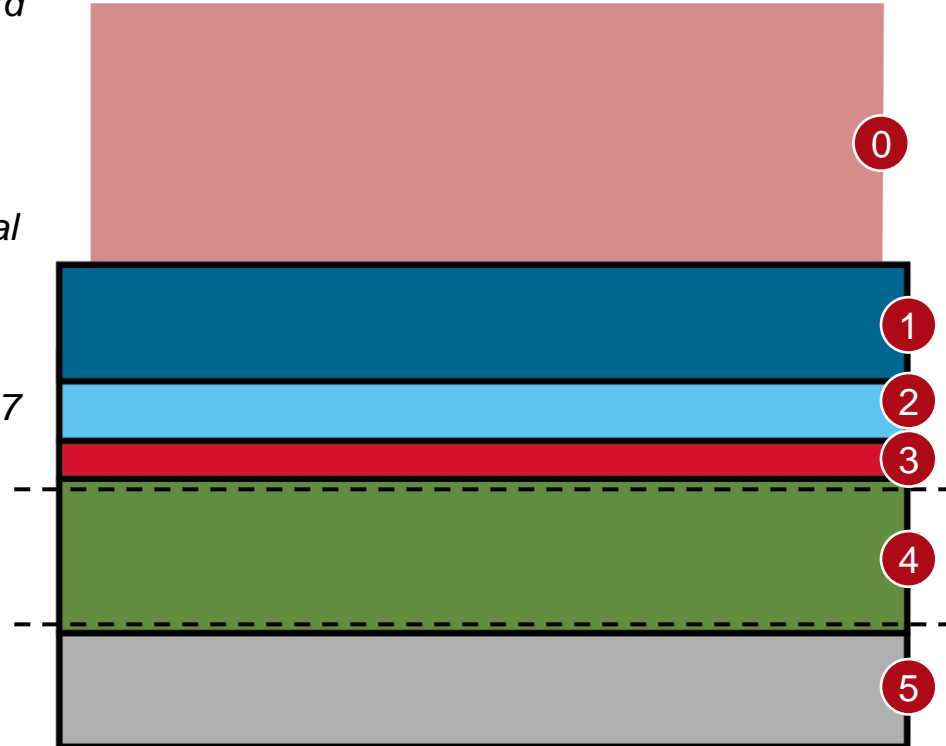
Solar cells are a fundamental technology in the field of renewable energy. To optimize efficiency, most common designs use thin-layer structures and media with high absorption coefficients – as it is precisely this absorbed optical energy what will eventually be transformed into an electric current. Solar cells based on copper indium gallium selenide (CIGS) have become quite common as they can be made much thinner without losing absorption efficiency, compared with cells based on other materials.

# Modeling Task

plane wave

homogeneous spectrum from 300nm to 1100nm

**System from:** J. Goffard et al., "Light Trapping in Ultrathin CIGS Solar Cells with Nanostructured Back Mirrors," in *IEEE Journal of Photovoltaics*, vol. 7, no. 5, pp. 1433-1441, Sept. 2017, doi: 10.1109/JPHOTOV.2017.2726566.



## detectors

radiant flux (absorbed power will be calculated as the difference between the radiant flux readings of both detectors)

## solar cell

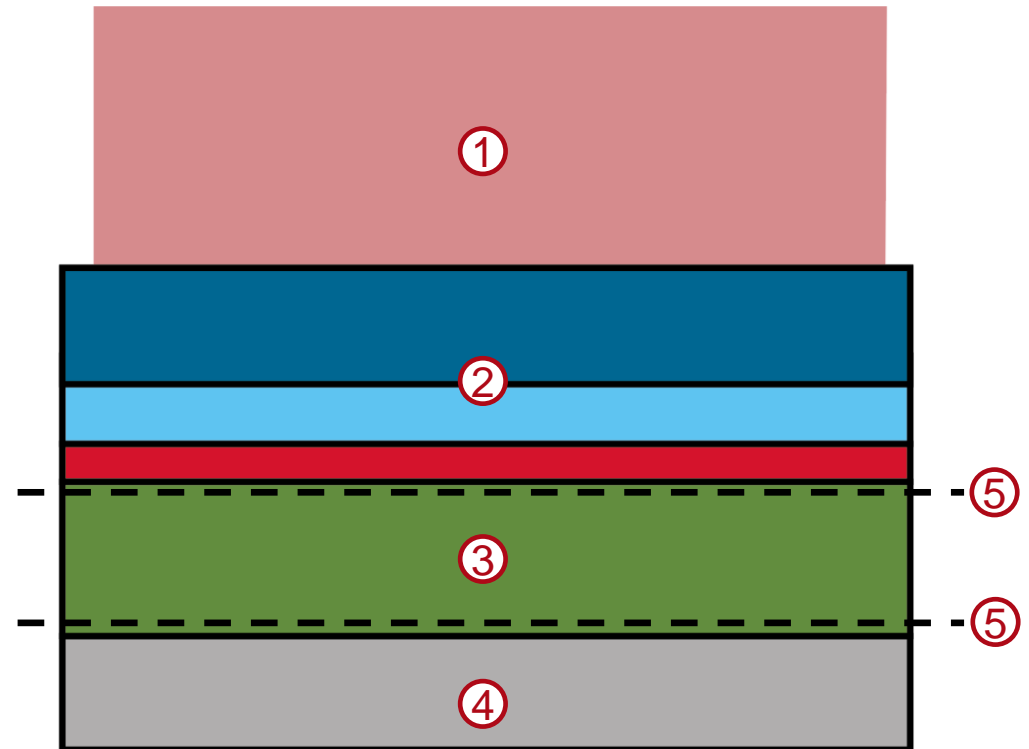
no.	material	thickness
0	fused silica*	-
1	ZnO:Al	100nm
2	i-ZnO	70nm
3	ZnS	50nm
4	CIGS	100/150/200nm
5	molybdenum	substrate

\* We assume that the solar cell is protected by a layer of fused silica with anti-reflection coating.

# Single-Platform Interoperability of Modeling Techniques

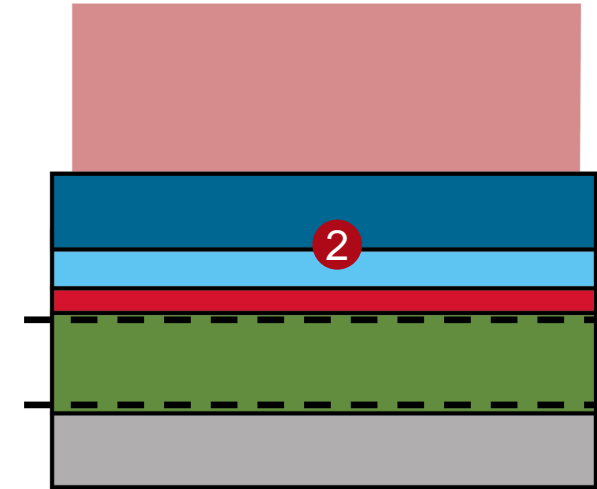
Light will encounter and interact with different components as it propagates through the system. A suitable model that provides a good compromise between accuracy and speed is required for each of these elements of the system:

- ① source
- ② solar cell layer
- ③ CIGS layer
- ④ Substrate
- ⑤ detector



# Connected Modeling Techniques: Solar Cell Layers

- ① source
- ② solar cell layers
- ③ CIGS layer
- ④ substrate
- ⑤ detectors



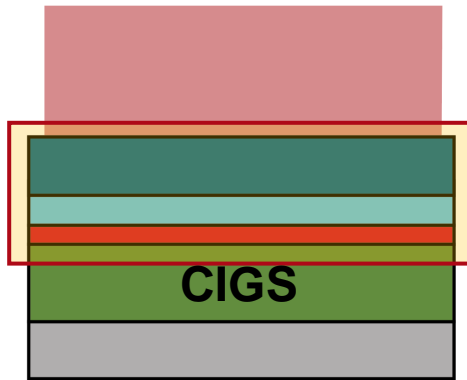
Available modeling techniques for multi-layer systems:

Methods	Preconditions	Accuracy	Speed	Comments
FMM/RCWA	none	high	high	rigorous model; includes evanescent waves; k-domain
S-matrix	planar surface	high	very high	rigorous model; includes evanescent waves; k-domain
Local Planar Interface Approximation	surface not in focal region of beam	high	high	local application of S matrix; LPIA; x-domain



Since the **S-matrix** solver operates entirely in the k-domain, no additional steps for switching between domains (Fourier transforms) are required for the application of this solver. This allows for the fastest possible simulation speed while maintaining a rigorous model.

# Stratified Media Component



For the layers above the CIGS we employ the *Stratified Media Component*, since it provides a fast and rigorous solution for x, y-invariant layer stacks.

The screenshot shows the 'Edit Stratified Media Component' software interface. The main window has a toolbar on the left with icons for Coordinate Systems, Position / Orientation, Structure, Solver, Channel Configuration, and Fourier Transforms. The main area contains settings for Component Size (20 mm x 20 mm), Reference Surface (all Channels), Plane Surface, Aperture (Yes/No), Coating Name (Standard Coating), Coating Orientation (Front Side Application), and Homogeneous Medium Behind Surface (CIGS in Homogeneous Medium). A 'Validity' indicator is at the bottom left.

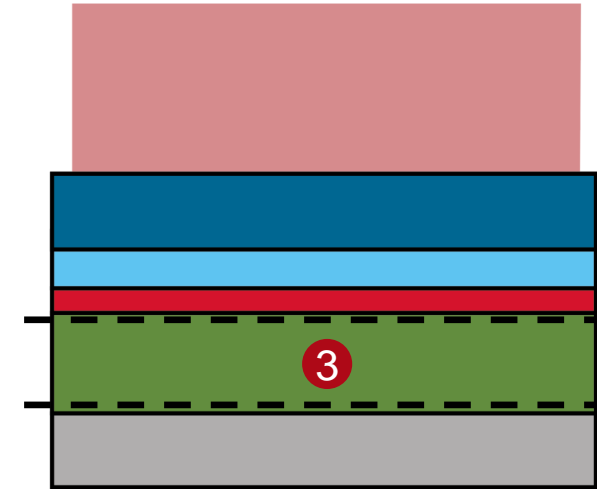
The 'Edit Parameters of Coating' dialog box is open, showing the 'Process Data' tab. It includes a diagram of a substrate with coating layers and a table of layer parameters.

Index	Thickness	Distance	Material
1	50 nm	50 nm	ZnS
2	70 nm	120 nm	i-ZnO
3	100 nm	220 nm	ZnO:Al

Below the table, there are buttons for 'Append', 'Insert', 'Delete', and 'Layer Tools'. At the bottom, there are input fields for 'Wavelength Range of Materials' with 'Minimum Wavelength' set to 300 nm and 'Maximum Wavelength' set to 1.125  $\mu\text{m}$ . The dialog box has 'OK', 'Cancel', and 'Help' buttons at the bottom right.

# Connected Modeling Techniques: CIGS Layers

- ① source
- ② solar cell layers
- ③ CIGS layer**
- ④ substrate
- ⑤ detectors



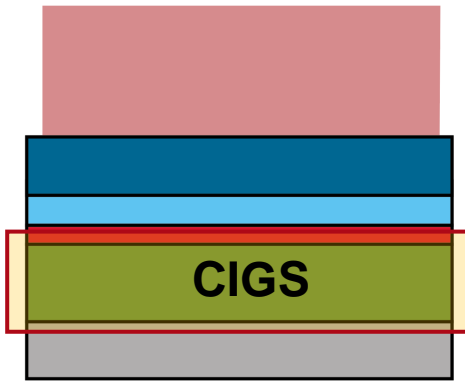
Available modeling techniques for free space propagation:

Methods	Preconditions	Accuracy	Speed	Comments
Rayleigh Sommerfeld Integral	none	high	low	rigorous solution
Fourier Domain Techniques	none	high	high	rigorous mathematical reformulation of RS integral
Fresnel Integral	paraxial	high	high	assumes paraxial light; moderate speed for very short distances
	non-paraxial	low	high	
Geometric Propagation	low diffraction	high	very high	neglects diffraction effects
	otherwise	low	very high	



The CIGS layer itself can be modeled by a single free-space propagation step in the corresponding homogeneous medium. Due to diffraction does not add any significant effects here, **Geometric Propagation** is used.

# Definition of Materials and Media



VirtualLab Fusion offers a comprehensive database of different materials that can, among other things, be used for coatings. But it is also possible to import material data from measurements, like ellipsometry.

The screenshot displays the 'Materials Catalog' window on the left, showing a tree view of materials under 'Photovoltaic' with 'CIGS' selected. The main window shows the 'CIGS' material properties, including a graph of 'Relative Refractive Index n' (blue line) and 'Absorption Coefficient  $\alpha$ ' (red line) versus 'Vacuum Wavelength' (nm). The graph shows a sharp increase in absorption around 0.45  $\mu\text{m}$  and a corresponding dip in the refractive index. Below the graph, the 'Valid Vacuum Wavelength Range' is set to 'Min. Wavelength: 275 nm'.

The 'Edit Material Data' window is open on the right, showing the 'CIGS' material name and the 'Refractive Index' tab. The 'Define Refractive Index by' section has 'Sampled Dispersion' selected. The 'Data' section shows a table of sampled dispersion data:

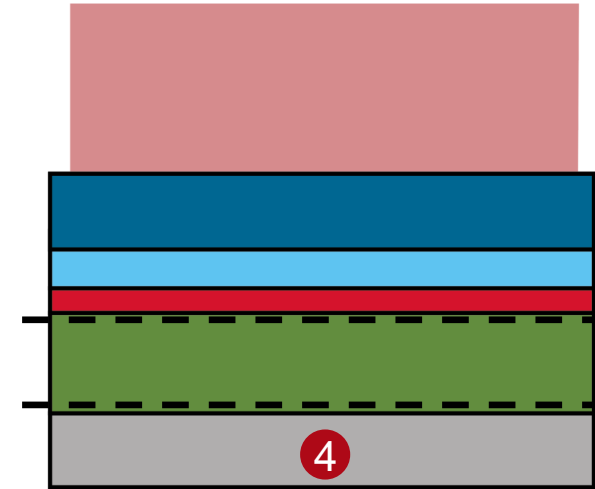
Wavelength	Real Refractive Index
636 nm	2.96
652 nm	2.96
670 nm	2.95
689 nm	2.96
708 nm	2.96
729 nm	2.96
751 nm	2.97
775 nm	2.97
800 nm	2.98
827 nm	2.99
855 nm	2.98
886 nm	2.98

The 'Domain of Definition' section shows the 'Vacuum Wavelength Range' set from 636 nm to 945 nm. The 'Usable Vacuum Wavelength Range' is shown as 636 nm to 925 nm. The 'Interpolation Method' is set to 'Linear Interpolation'.



# Connected Modeling Techniques: Substrate

- ① source
- ② solar cell layers
- ③ CIGS layer
- ④ substrate
- ⑤ detectors



Available modeling techniques for interaction with surface:

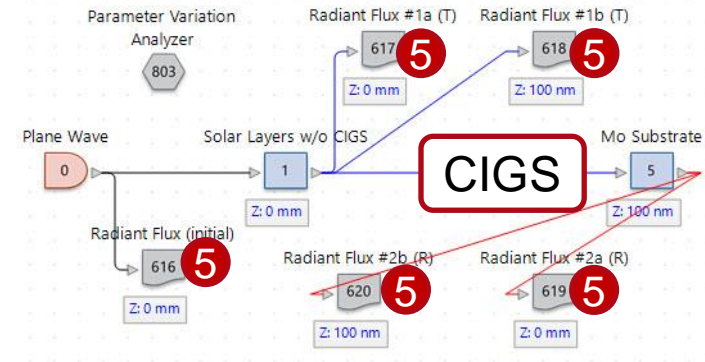
Methods	Preconditions	Accuracy	Speed	Comments
functional approach	-	low	very high	no Fresnel losses
S-matrix	planar surface	high	high	rigorous model; includes evanescent waves; k-domain
Local Planar Interface Approximation	surface not in focal region of beam	high	high	local application of S matrix; LPIA; x-domain



For our simulation, only the reflection of the substrate is of interest, reducing the problem to an interaction with a single surface. Here, **Local Planar Interface Approximation** provides the best compromise between speed and accuracy.

# Connected Modeling Techniques: Detectors

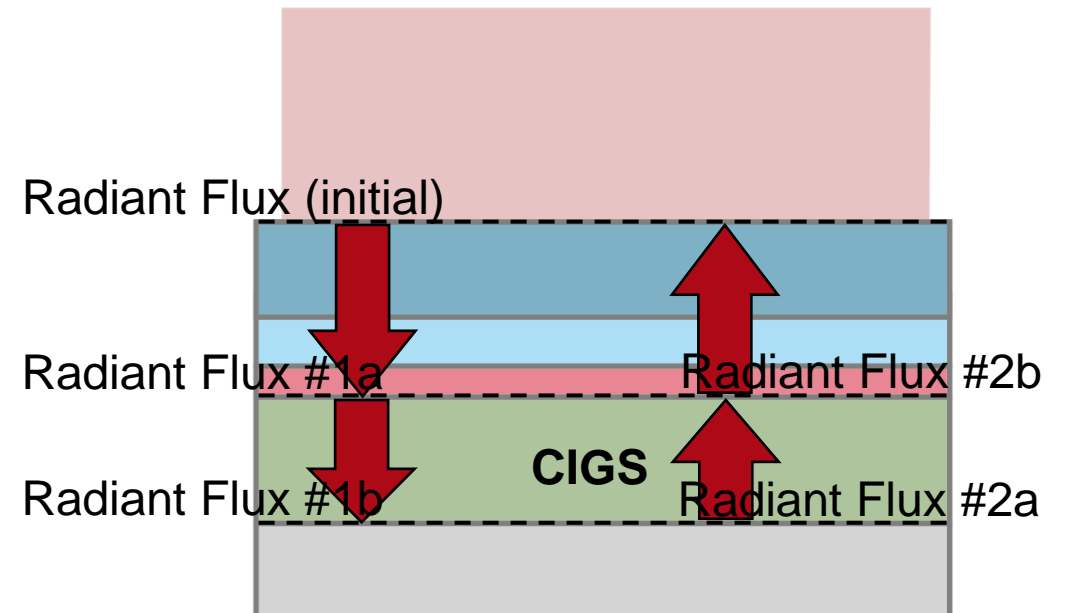
- ① source
- ② solar cell layers
- ③ CIGS layer
- ④ substrate
- ⑤ detectors



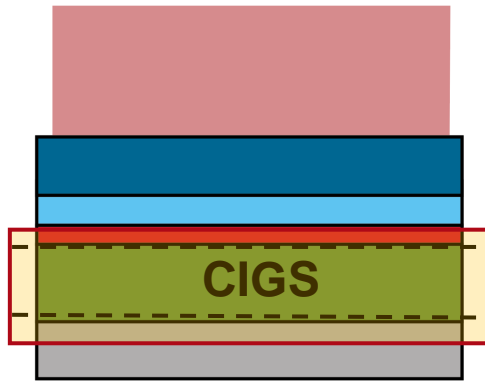
The absorbed energy inside the CIGS layer per wavelength is determined by adding/subtracting the values of the radiant flux from 4 different *Universal Detectors*: before the CIGS layer: 1a(**T**ransmitted part) and 2a(**R**eflected part), behind: 1b and 2b.

$$\text{absorbed energy} = 1b - 1a + 2b - 2a$$

These values are then normalized by the initial radiant flux to get the absorption ratio.



# Parameter Variation Analyzer



With the *Parameter Variation Analyzer*, the addition/subtraction can be done automatically, outputting the resulting absorption by a single simulation. For more information, see:

[Parameter Variation Analyzer](#)

The screenshot shows the '6: Edit Parameter Variation' dialog box. The 'Parameter Specification' section includes a 'Usage Mode' dropdown set to 'Standard' and a 'Filter by...' search box. A table lists the parameters to be varied:

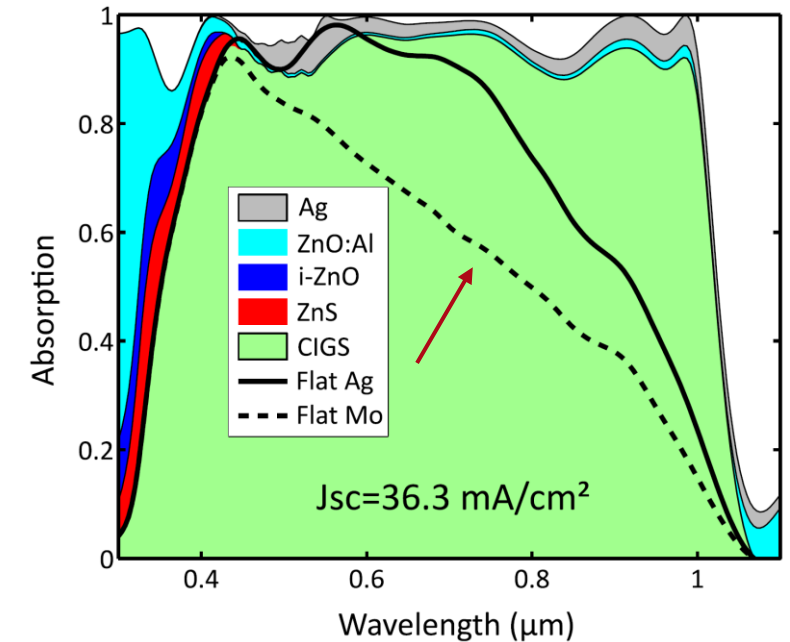
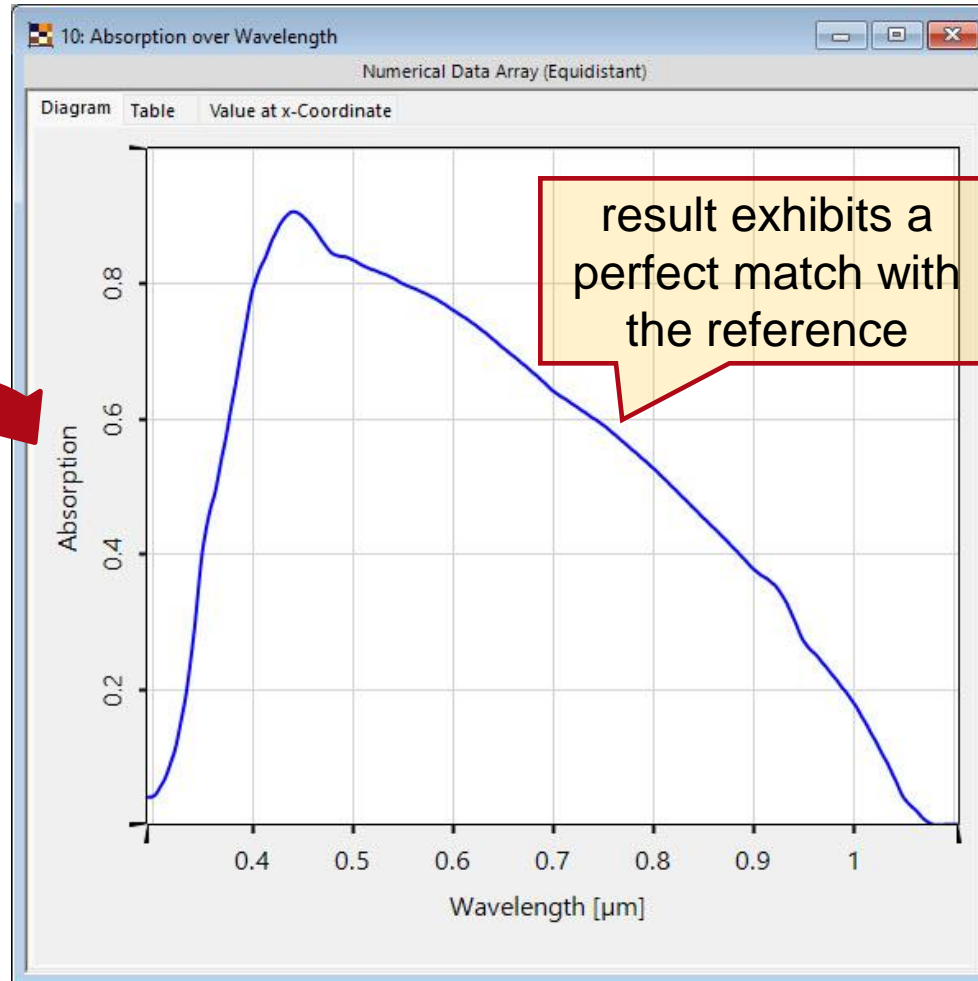
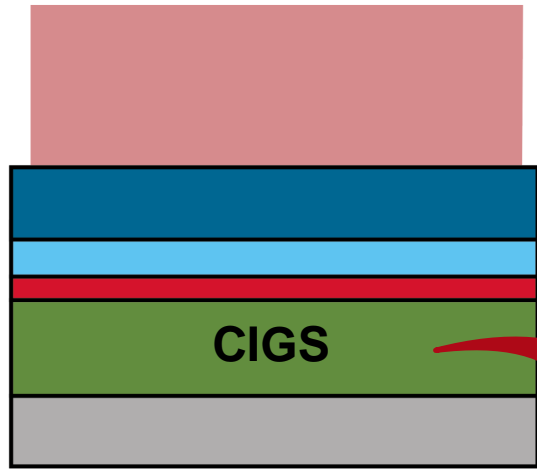
1	2	*	Object	Category	Parameter	Vary	From	To	Steps	Step Size	Original Value
			"Plane Wave" (# 0)		Wavelength	<input checked="" type="checkbox"/>	300 nm	1.1 $\mu$ m	81	10 nm	900 nm

Below the table is a 'Source Code Editor' window showing the following code:

```
1  Preset using directives
26
27  #region Additional using directives
28
29  #endregion
30
31  Base class to handle Global Parameters
63
64  public class VLModule : VLBaseModule, VirtualLabAPI.Core.Modules.ISnippet_F
65
66  public List<DetectorResultObject> GetData(VirtualLabAPI.Core.ParameterF
67
68  #region Main method
69
70  ParameterVariation.StartParameterRun();
71
72  string searchString_detectorName1 = "Power #1a (T)";
73  string searchString_detectorName2 = "Power #1b (T)";
74  string searchString_detectorName3 = "Power #2a (R)";
75  string searchString_detectorName4 = "Power #2b (R)";
76  string searchString_detectorName5 = "Power (initial)";
77
78
```

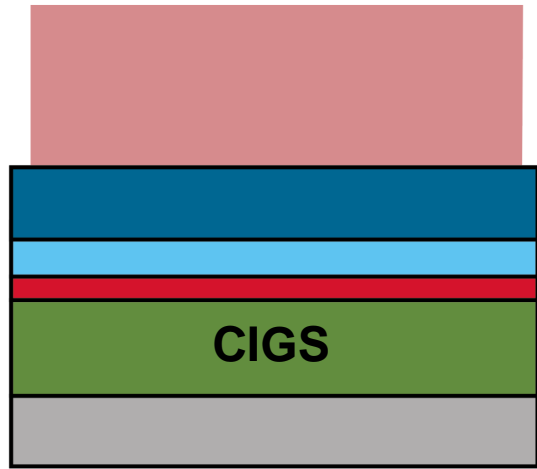
The interface also includes 'Check Consistency', 'Validity' (with a warning icon), and 'OK', 'Cancel', 'Help' buttons.

# Absorption for Different Thicknesses of the CIGS Layer



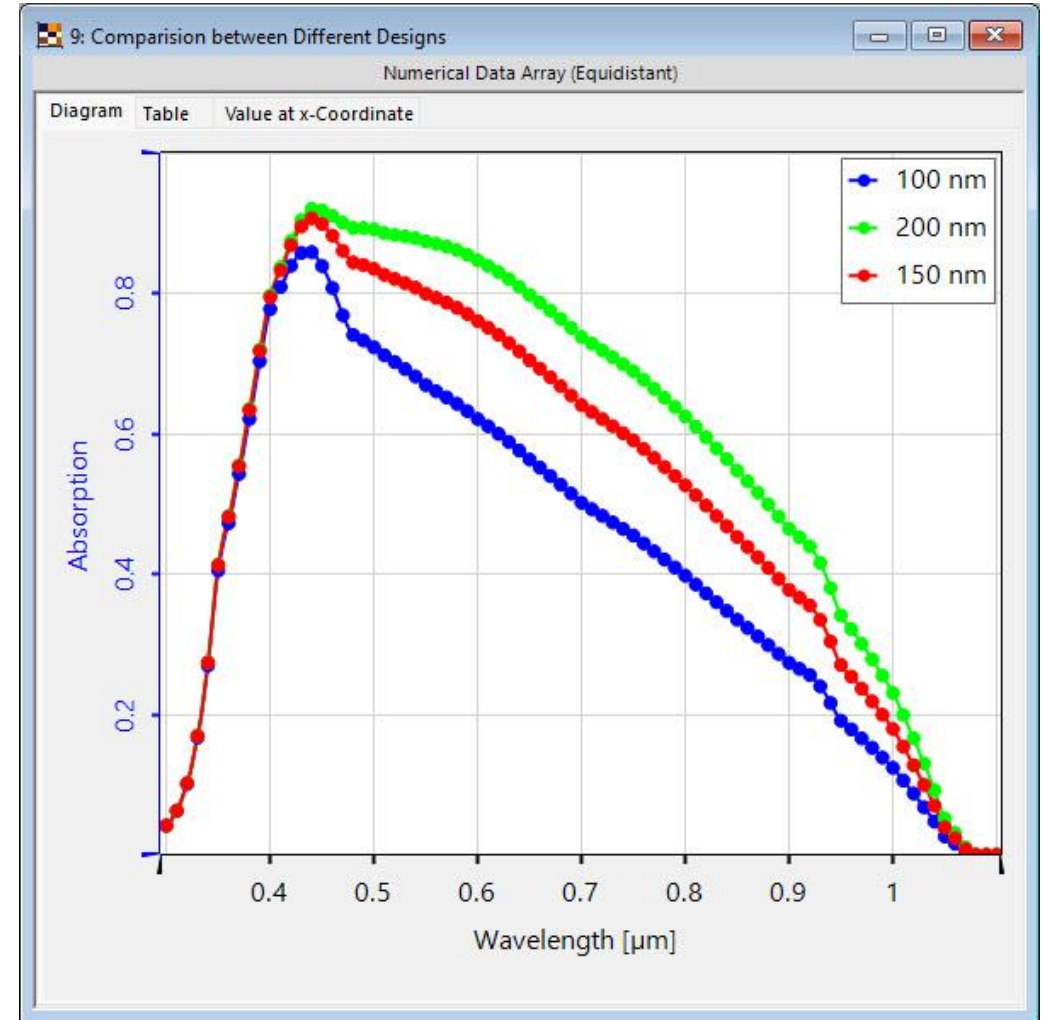
**Reference:** J. Goffard et al., "Light Trapping in Ultrathin CIGS Solar Cells with Nanostructured Back Mirrors," in *IEEE Journal of Photovoltaics*, vol. 7, no. 5, pp. 1433-1441, Sept. 2017, doi: 10.1109/JPHOTOV.2017.2726566.

# Absorption for Different Thicknesses of the CIGS Layer



variation of thickness  
of CIGS layer:  
100/150/200 nm

The thickness of the absorbing material is one of the most important parameters affecting the overall efficiency of the cell.



# Document Information

title	Absorption in a CIGS Solar Cell
document code	MISC.0096
document version	1.1
software edition	VirtualLab Fusion
software version	2023.2 (Build 1.242)
category	Application Use Case
further reading	<ul style="list-style-type: none"><li>- <a href="#">Stratified Media Component</a></li><li>- <a href="#">Parameter Variation Analyzer</a></li></ul>