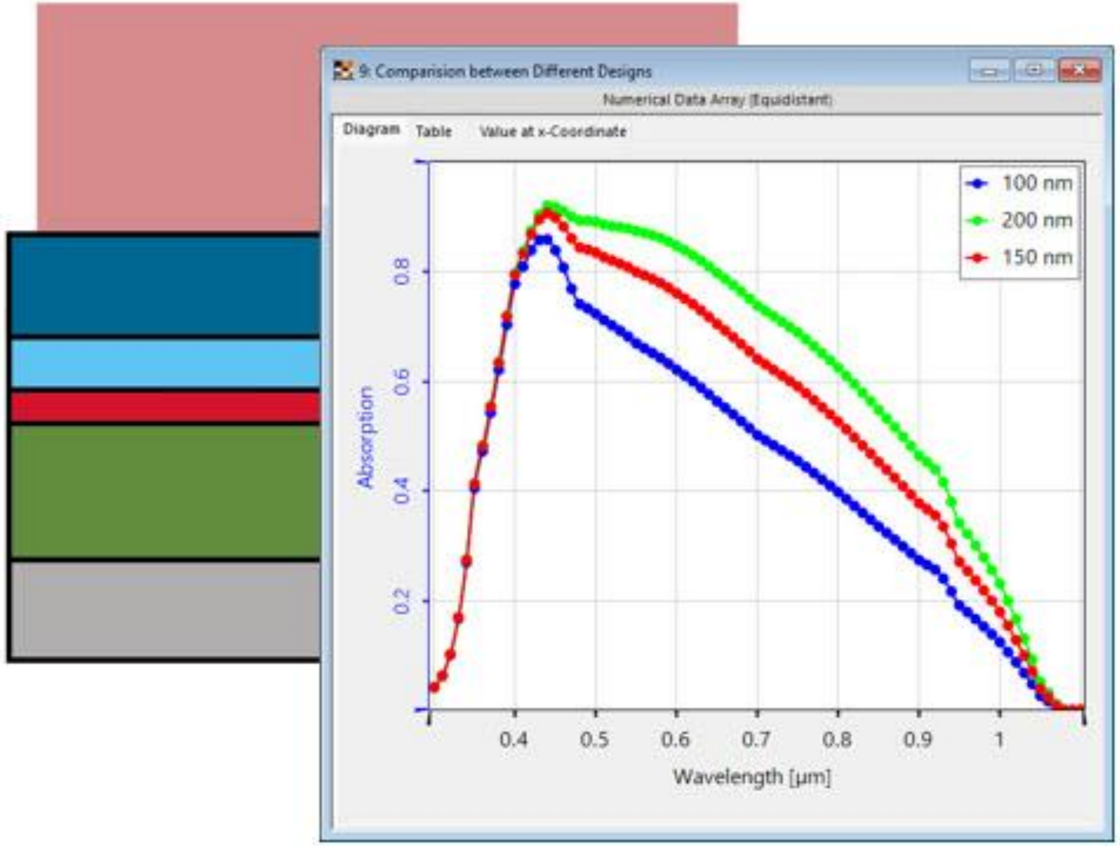
# Absorption in a CIGS Solar Cell

# Abstract



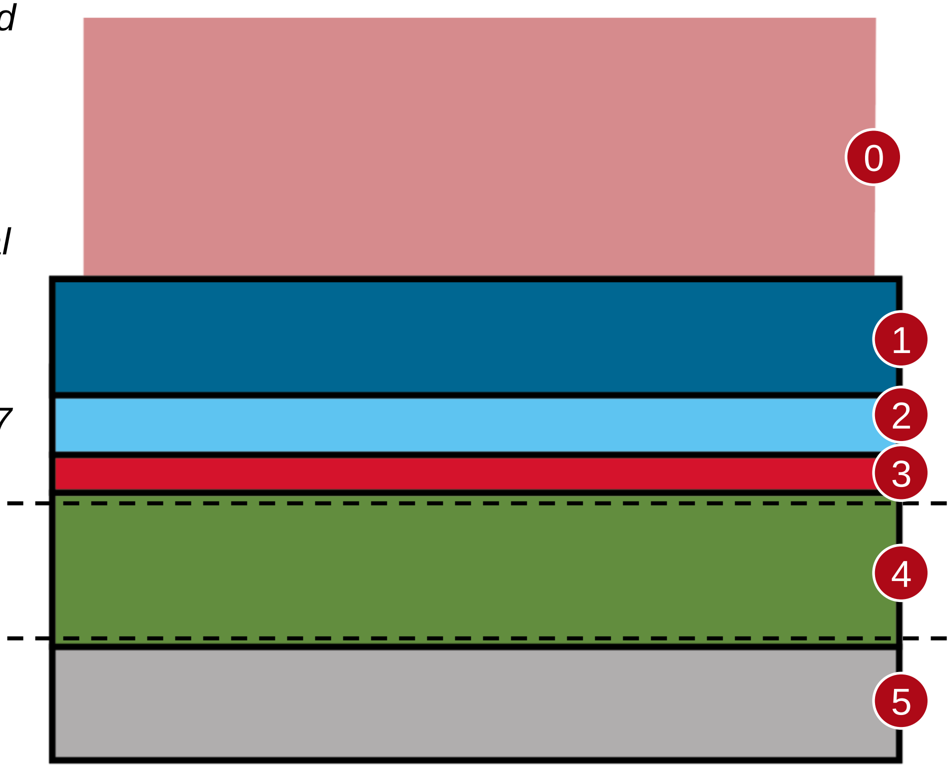
Solar cells are a fundamental technology in the field of renewable energy. To optimize efficiency, most common designs use thin-layer structures and media with high absorption coefficients – as it is precisely this absorbed optical energy what will eventually be transformed into an electric current. 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 300 nm to 1100 nm

***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.*



**solar cell**

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

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

**detectors**

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

# 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:

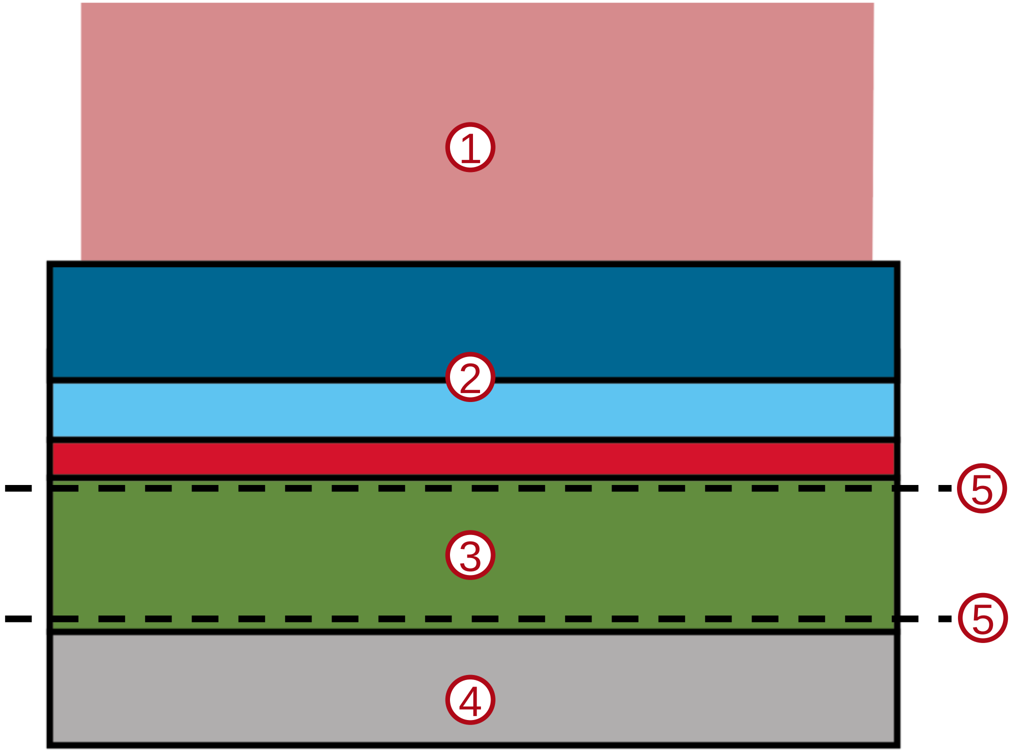
① source

② solar cell layer

③ CIGS layer

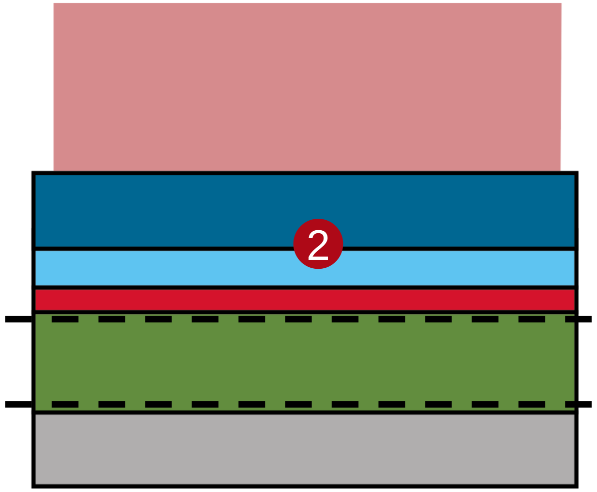
④ Substrate

⑤ detector



# Connected Modeling Techniques: Solar Cell Layers

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

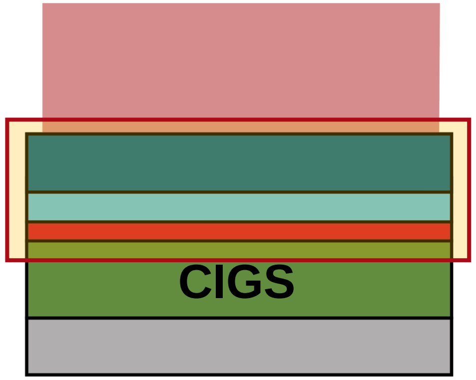


Available modeling techniques for multi-layer systems:

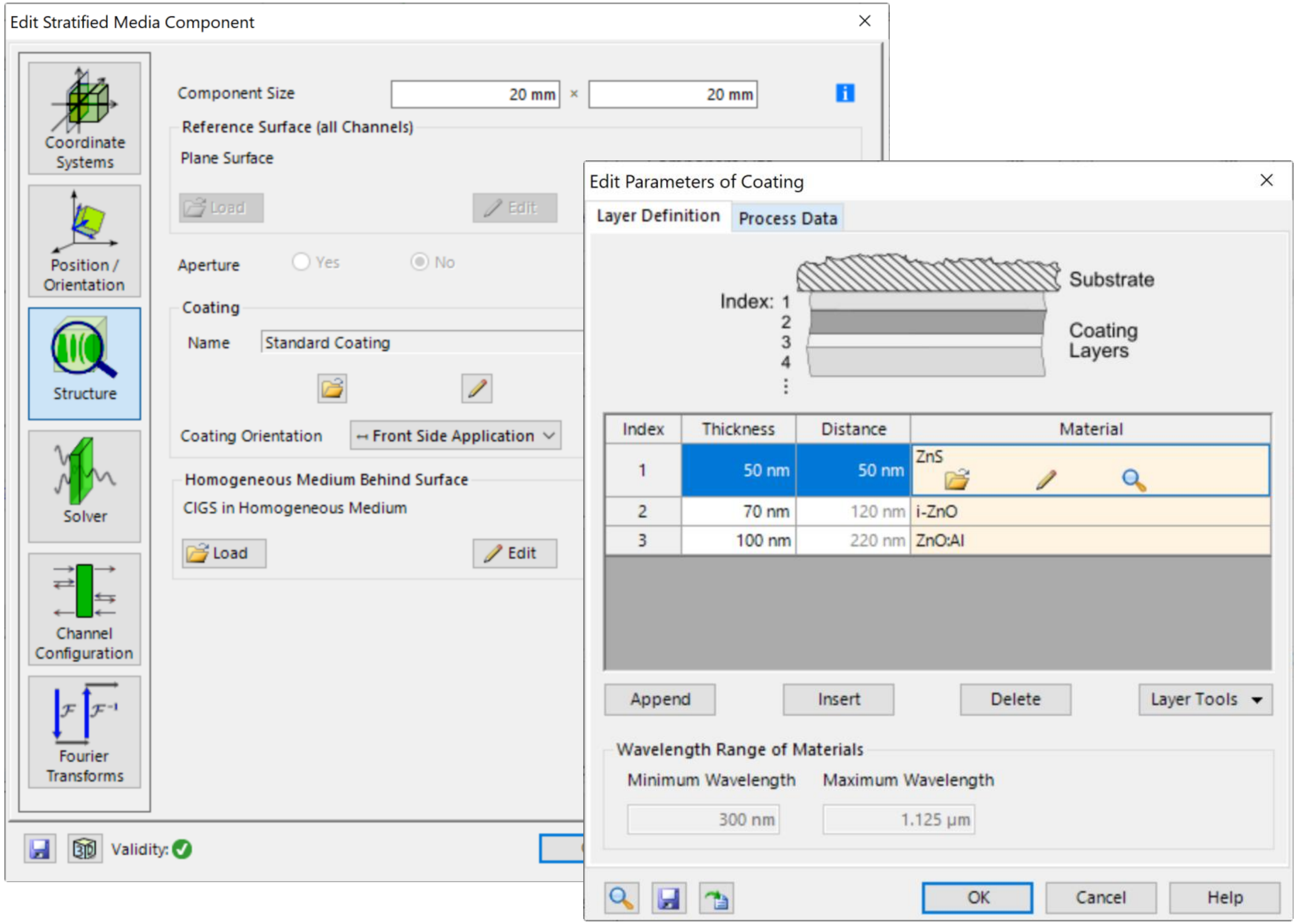
| Methods | Preconditions | Accuracy | Speed | Comments |
|---|---|---|---|---|
| FMM/RCWA | none | high | high | rigorous model; includes evanescent waves; k-domain |
| S-matrix | planar surface | high | very high | rigorous model; includes evanescent waves; k-domain |
| Local Planar Interface Approximation | 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.



Component Size: 20 mm × 20 mm

Reference Surface (all Channels): Plane Surface

Aperture: ○ Yes ● No

Coating
Name: Standard Coating

Coating Orientation: Front Side Application

Homogeneous Medium Behind Surface: CIGS in Homogeneous Medium

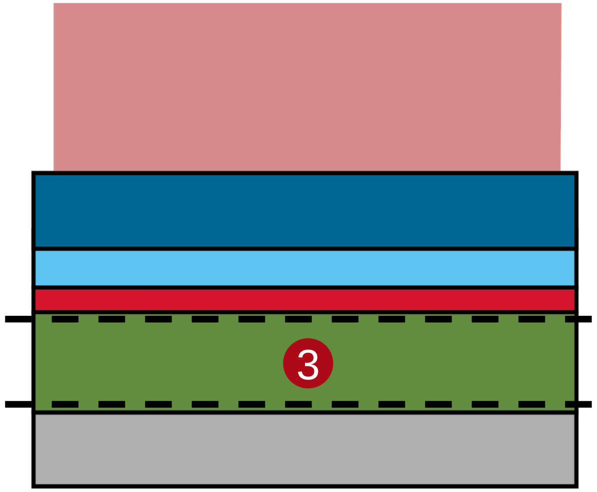
Validity: ✓

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

Wavelength Range of Materials
Minimum Wavelength: 300 nm
Maximum Wavelength: 1.125 µm

# Connected Modeling Techniques: CIGS Layers

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

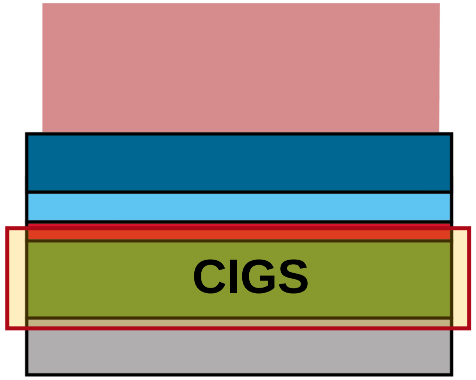


Available modeling techniques for free space propagation:

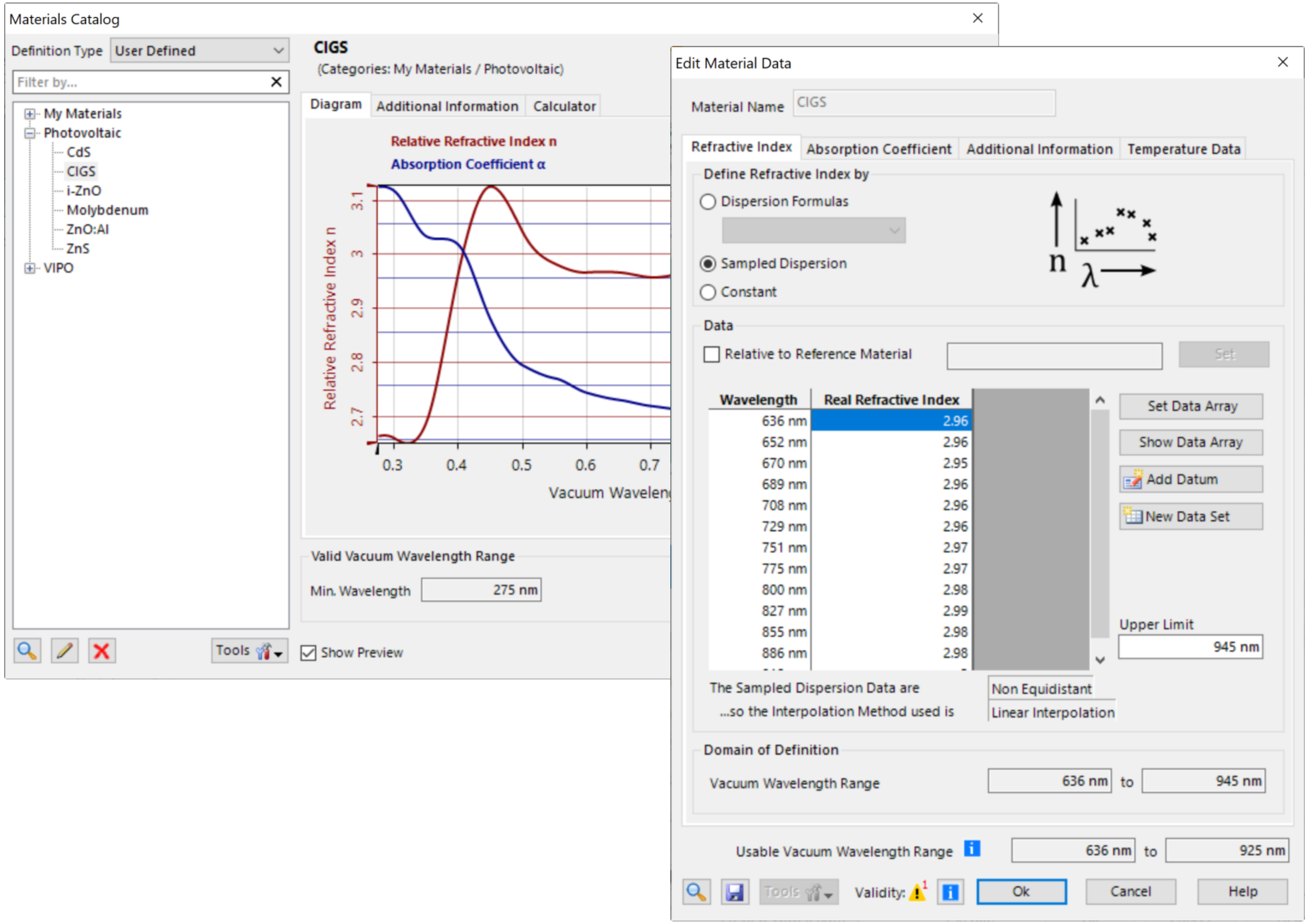
| Methods | Preconditions | Accuracy | Speed | Comments |
|---|---|---|---|---|
| Rayleigh Sommerfeld Integral | none | high | low | rigorous solution |
| Fourier Domain Techniques | none | high | high | rigorous mathematical reformulation of RS integral |
| Fresnel Integral | paraxial | high | high | 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.



Definition Type: User Defined

**CIGS**
(Categories: My Materials / Photovoltaic)

Valid Vacuum Wavelength Range
Min. Wavelength: 275 nm

☑ Show Preview

Material Name: CIGS

Define Refractive Index by
○ Dispersion Formulas
● Sampled Dispersion
○ Constant

Data
☐ Relative to Reference Material

| 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 |

Upper Limit: 945 nm

The Sampled Dispersion Data are: Non Equidistant
...so the Interpolation Method used is: Linear Interpolation

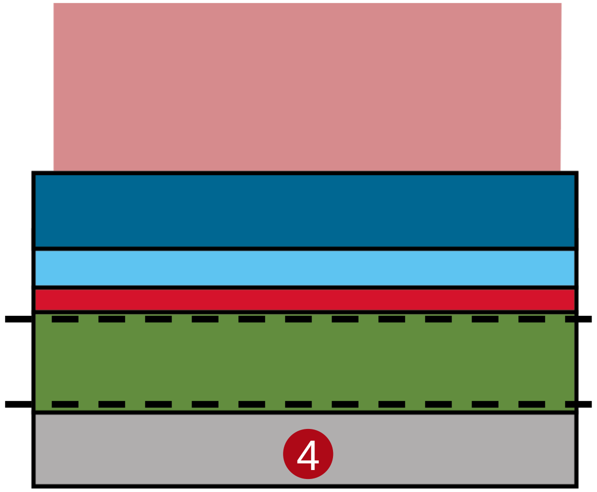
Domain of Definition
Vacuum Wavelength Range: 636 nm to 945 nm

Usable Vacuum Wavelength Range: 636 nm to 925 nm

Validity: ⚠

# Connected Modeling Techniques: Substrate

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



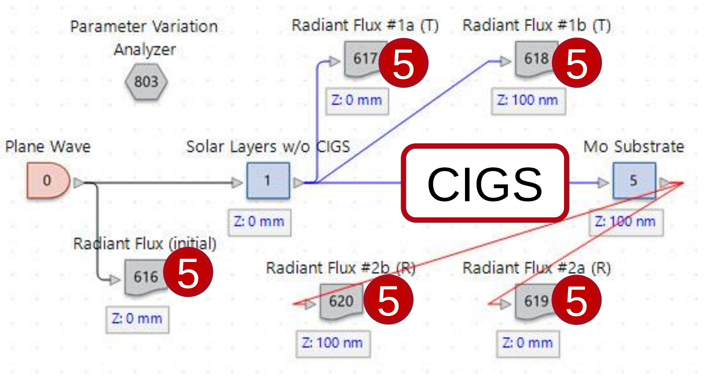
Available modeling techniques for interaction with surface:

| 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

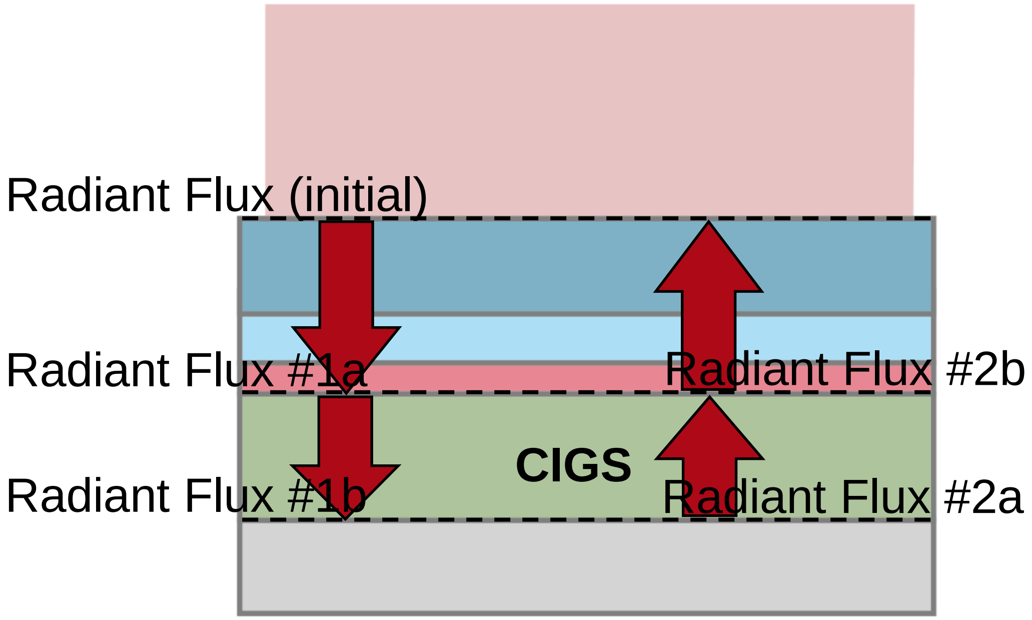
① source
② solar cell layers
③ CIGS layer
④ substrate
⑤ detectors



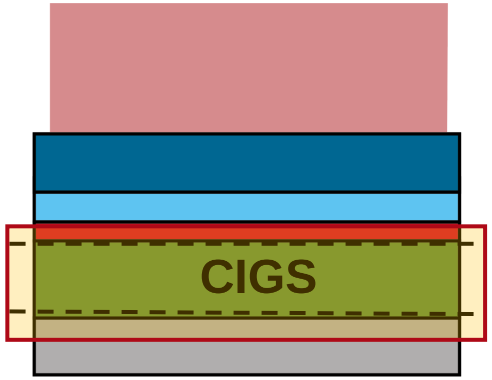
The absorbed energy inside the CIGS layer per wavelength is determined by adding/subtracting the values of the radiant flux from 4 different *Universal Detectors*: before the CIGS layer: 1a(**T**ransmitted part) and 2a(**R**eflected part), behind: 1b and 2b.

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

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

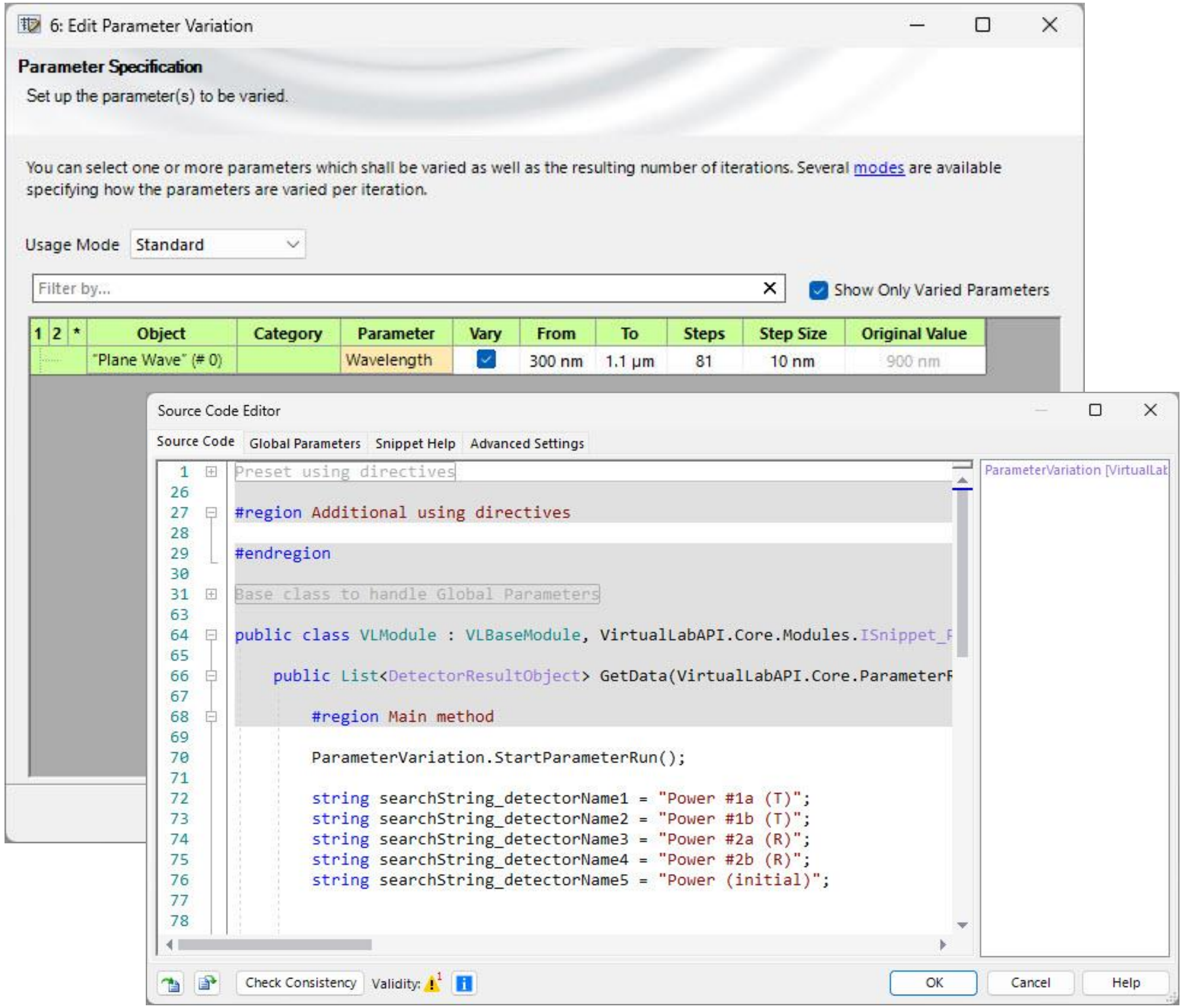


# Parameter Variation Analyzer



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]()



**Parameter Specification**

Set up the parameter(s) to be varied.

You can select one or more parameters which shall be varied as well as the resulting number of iterations. Several modes are available specifying how the parameters are varied per iteration.

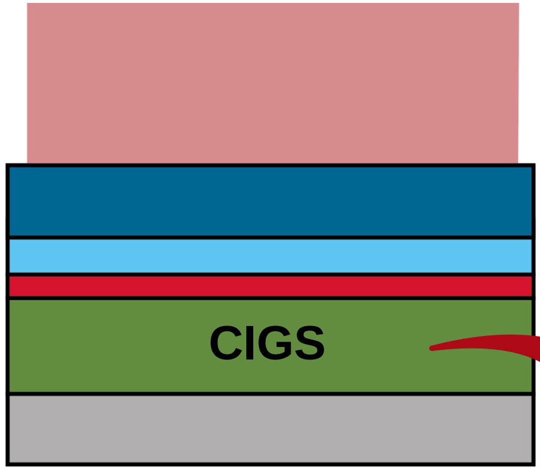
Usage Mode: Standard

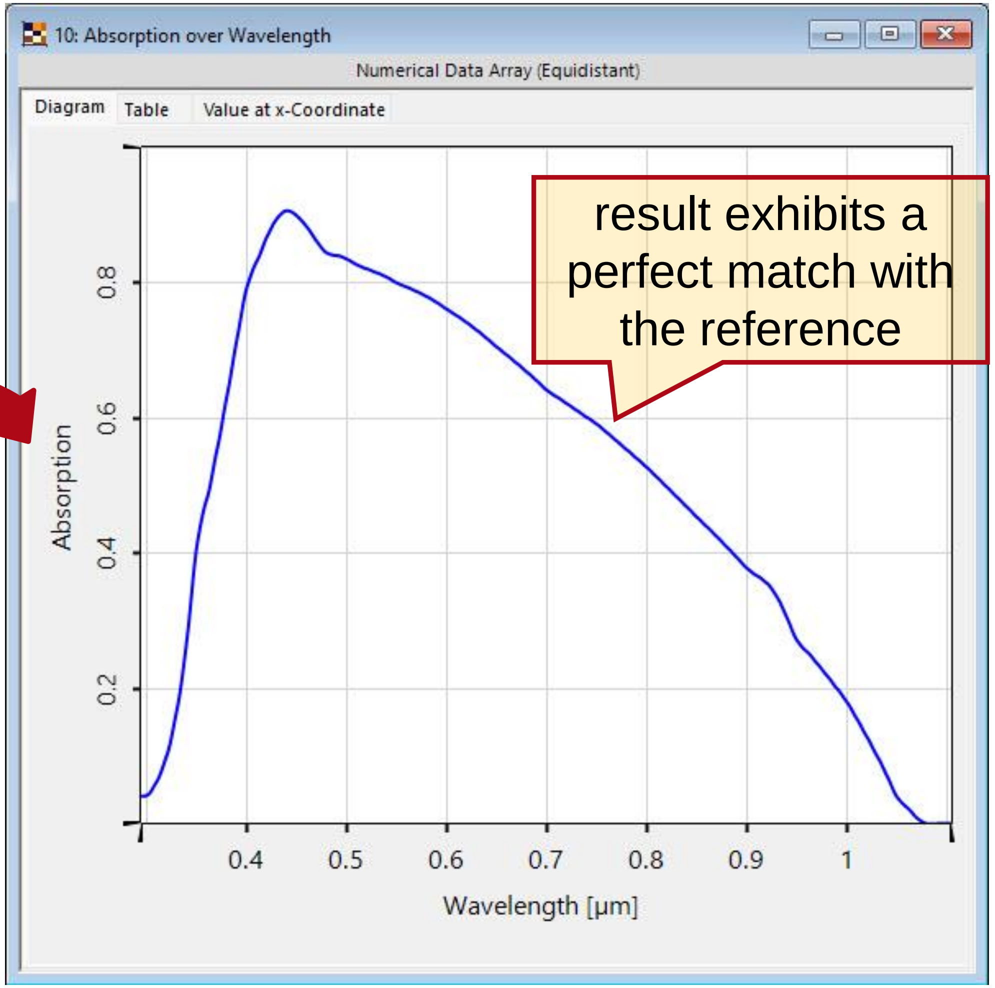
☑ Show Only Varied Parameters

| 1 | 2 | * | Object | Category | Parameter | Vary | From | To | Steps | Step Size | Original Value |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | "Plane Wave" (# 0) | | Wavelength | ☑ | 300 nm | 1.1 µm | 81 | 10 nm | 900 nm |

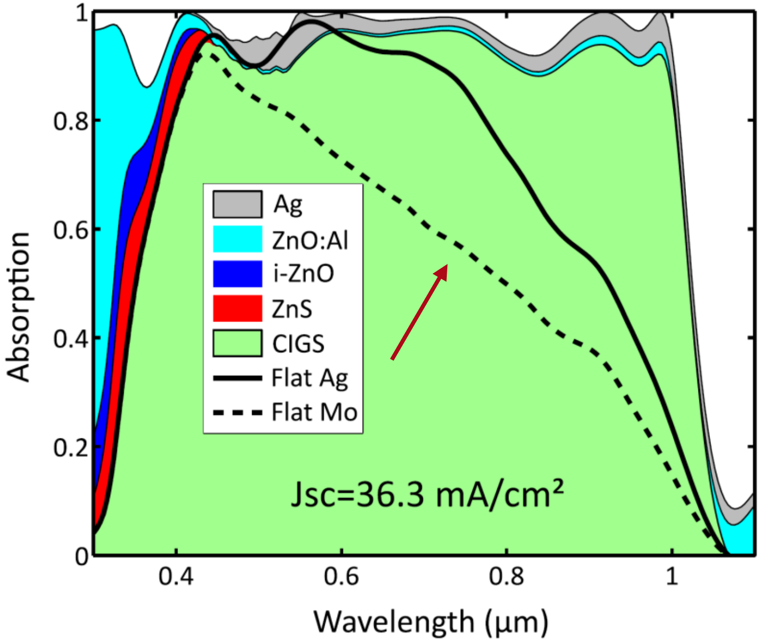
```
Preset using directives

#region Additional using directives

#endregion

Base class to handle Global Parameters

public class VLModule : VLBaseModule, VirtualLabAPI.Core.Modules.ISnippet_

    public List<DetectorResultObject> GetData(VirtualLabAPI.Core.Parameter

        #region Main method

        ParameterVariation.StartParameterRun();

        string searchString_detectorName1 = "Power #1a (T)";
        string searchString_detectorName2 = "Power #1b (T)";
        string searchString_detectorName3 = "Power #2a (R)";
        string searchString_detectorName4 = "Power #2b (R)";
        string searchString_detectorName5 = "Power (initial)";
```

# Absorption for Different Thicknesses of the CIGS Layer





result exhibits a perfect match with the reference



***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.*

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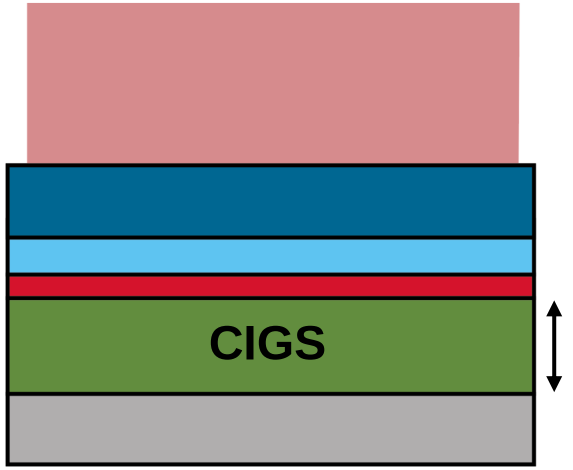
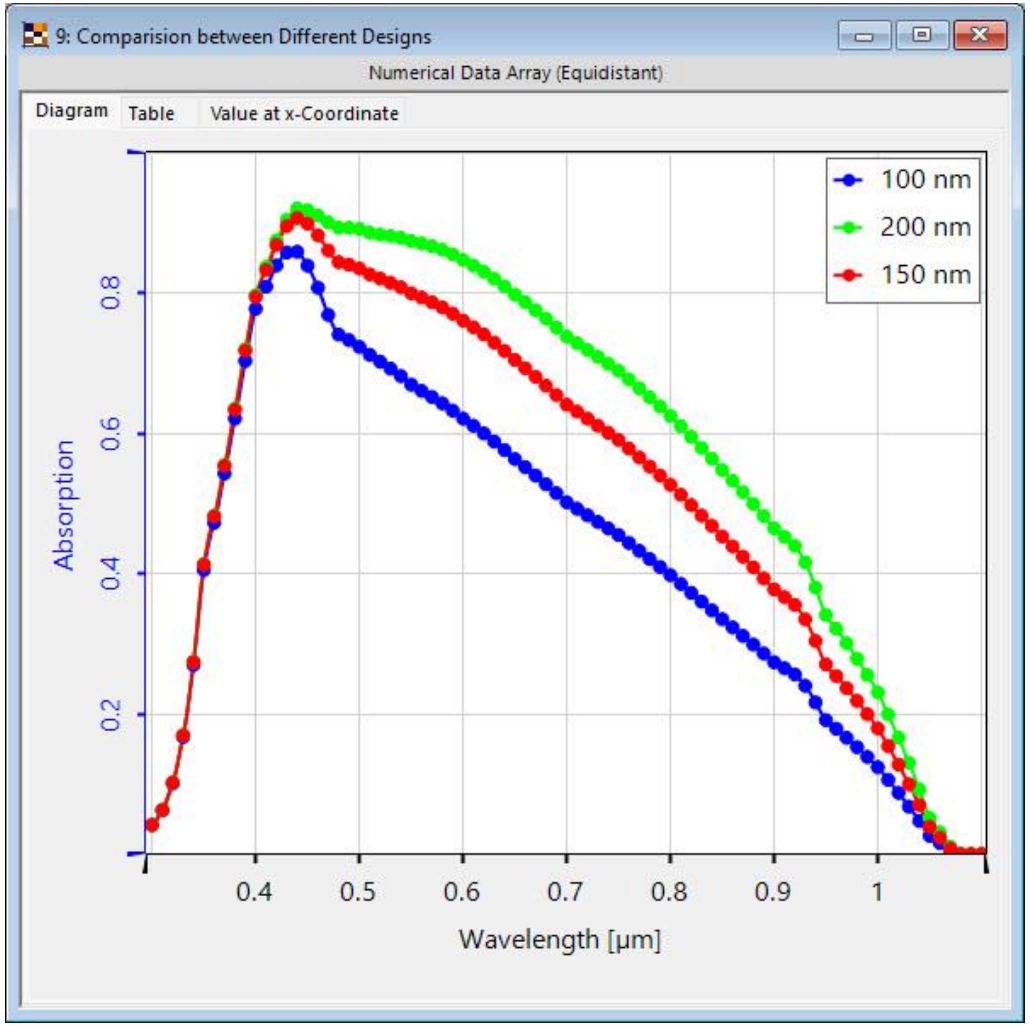


variation of thickness
of CIGS layer:
100/150/200 nm

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



# Document Information

| | |
|---|---|
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| software version | 2023.2 (Build 1.242) |
| category | Application Use Case |
| further reading | - Stratified Media Component<br>- Parameter Variation Analyzer |