Tutorial 1

Analysis of Bianisotropic Slabs with E2M-Win

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Introduction

The purpose of this document is to guide users through the core functionalities of E2M-Win. In **Tutorial 1**, we validate the software's accuracy by reproducing the Reflectance (R), Transmittance (T), and Absorptance (A) spectra of a bianisotropic medium.

We reference the seminal text, *"The Transfer-Matrix Method in Electromagnetics and Optics"* by Tom G. Mackay and Akhlesh Lakhtakia. Since the authors provide source codes to reproduce their findings, comparing E2M-Win's results with this reference data serves as an excellent benchmark for verification.

This tutorial provides a step-by-step guide to modeling the suggested structure, ensuring users can easily follow the workflow.

Summary of Objectives:

1. **Training:** Learning how to use E2M-Win to analyze layers containing bianisotropic materials.
2. **Benchmarking:** Reproduce **Figure 3.2** from *"The Transfer-Matrix Method in Electromagnetics and Optics"* (Mackay & Lakhtakia).

By completing this tutorial, users will gain proficiency in using E2M-Win to analyze bianisotropic slabs defined by full constitutive tensors ($[\varepsilon]$, $[\mu]$, $[\zeta]$, $[\xi]$). The reproduced results are presented on the following page.

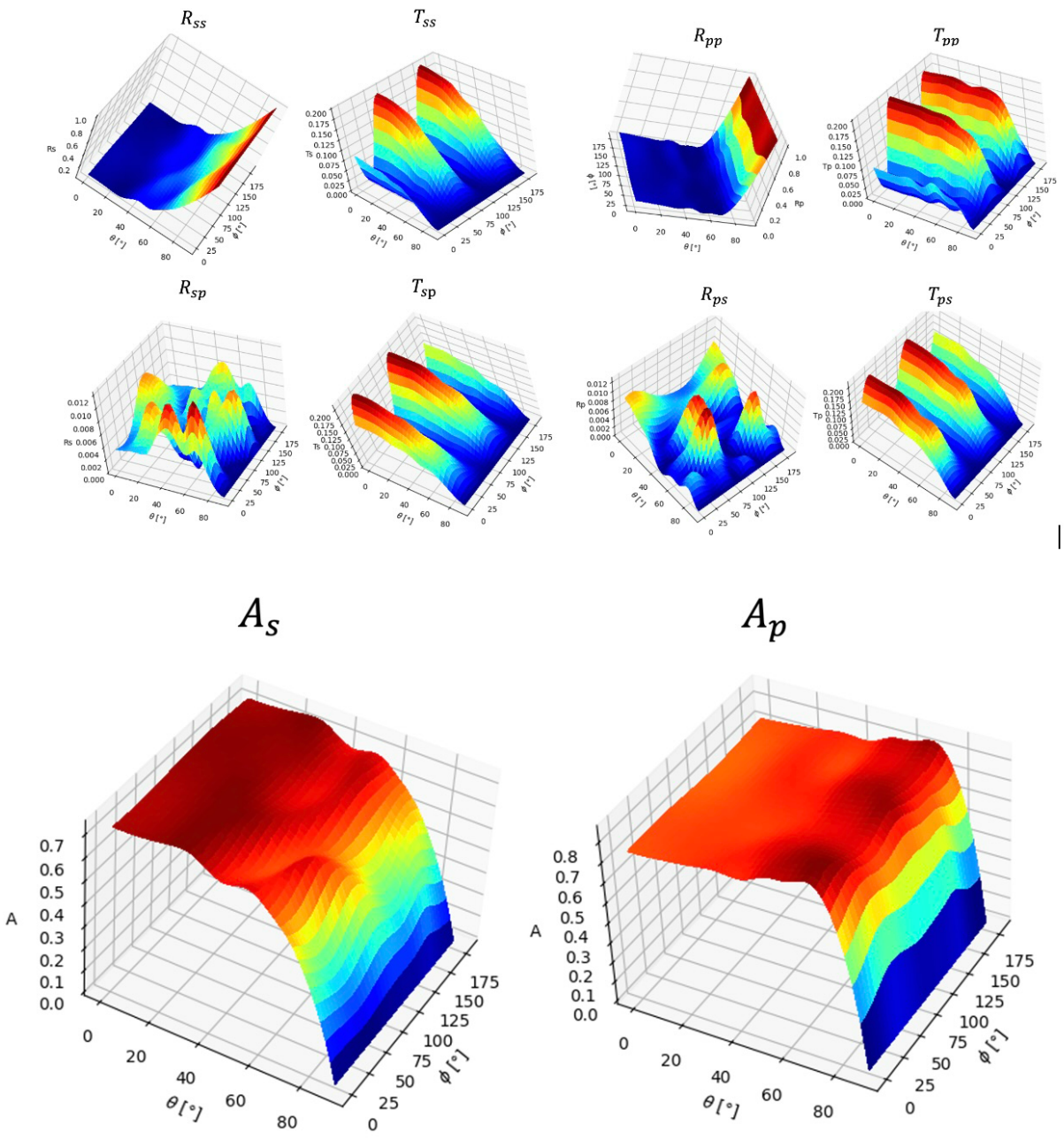

Figure 1. Recalculated results for the reference by using E2M-Win.

[Step1: Start a New Project]

1. **Launch E2M-Win** by double-clicking the application icon as shown in Figure 2.

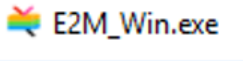

Figure 2. File icon of E2M-Win

2. Wait for the initialization to complete. The main interface will appear as shown in Figure 3.

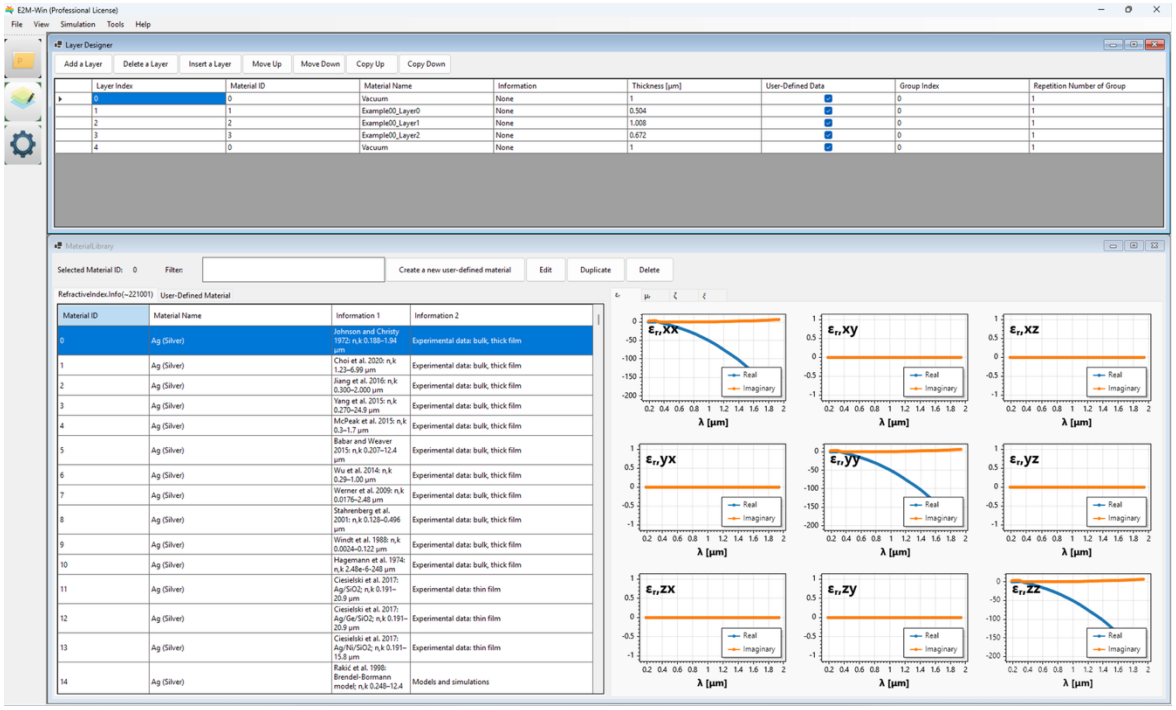

Figure 3. Main interface structure of E2M-Win

3. Click the folder icon like Figure 4 on the left-side menu (or press **F2** shortcut key) to designate a project folder.

Figure 4. Icon for "Create/Select Project Folder" menu

4. Select the directory where your save files will be stored with a dialog as shown in Figure 5.

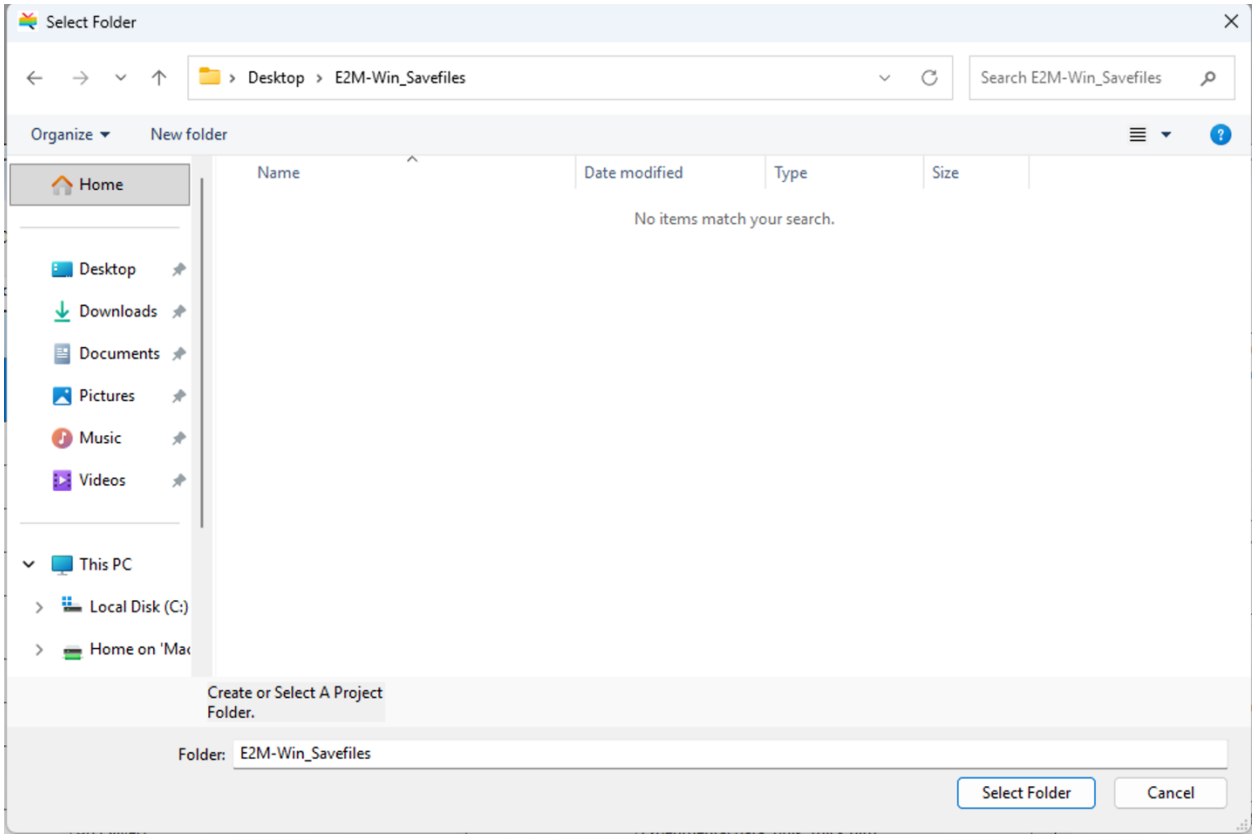

Figure 5. "Select Folder" dialog

5. Once the folder is selected, a message box like Figure 6 appears. Click **OK** on the message box.

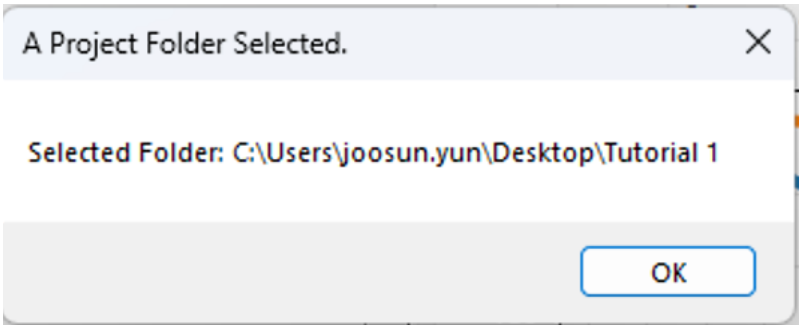

Figure 6. Confirmation message box after a project folder is selected.

6. The selected project path will now be displayed as shown in Figure 7 in the top title bar.

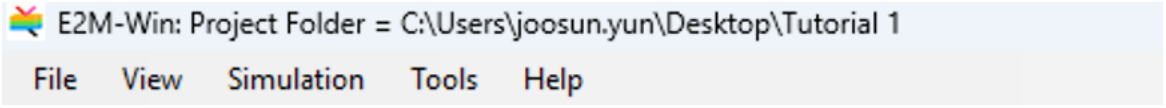

Figure 7. Changed title bar after the selection of project folder.

[Step2: Create and Prepare Materials]

The target reference requires four specific material parameters described by the tensors below.

- Material 1:

$$[\varepsilon_{r,1}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, [\mu_{r,1}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, [\zeta_{r,1}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, [\xi_{r,1}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- Material 2:

$$[\varepsilon_{r,2}] = \begin{bmatrix} 2.9 - 0.04i & 0 & 0 \\ 0 & 2.5 - 0.03i & 0 \\ 0 & 0 & 2.1 - 0.02i \end{bmatrix},$$

$$[\mu_{r,2}] = \begin{bmatrix} 1.1 - 0.025i & 0 & 0 \\ 0 & 1.05 - 0.015i & 0 \\ 0 & 0 & 1.02 - 0.012i \end{bmatrix},$$

$$[\zeta_{r,2}] = \begin{bmatrix} 0.0008 + 0.1i & 0 & 0 \\ 0 & 0.0006 + 0.07i & 0 \\ 0 & 0 & 0.0005 + 0.06i \end{bmatrix},$$

$$[\xi_{r,2}] = \begin{bmatrix} -0.0008 - 0.1i & 0 & 0 \\ 0 & -0.0006 - 0.07i & 0 \\ 0 & 0 & -0.0005 - 0.06i \end{bmatrix}$$

- Material 3:

$$[\varepsilon_{r,3}] = \begin{bmatrix} 2.4 - 0.03i & 0 & 0 \\ 0 & 1.9 - 0.02i & 0 \\ 0 & 0 & 2.4 - 0.03i \end{bmatrix},$$

$$[\mu_{r,3}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, [\zeta_{r,3}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, [\xi_{r,3}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

- Material 4:

$$[\varepsilon_{r,4}] = \begin{bmatrix} 4.1 - 0.08i & 0.005 + 0.8i & 0 \\ -0.005 - 0.8i & 4.1 - 0.08i & 0 \\ 0 & 0 & 3.4 - 0.06i \end{bmatrix},$$

$$[\mu_{r,4}] = \begin{bmatrix} 1.3 - 0.04i & 0.003 + 0.35i & 0 \\ -0.003 - 0.35i & 1.3 - 0.04i & 0 \\ 0 & 0 & 1.1 - 0.03i \end{bmatrix},$$

$$[\zeta_{r,4}] = \begin{bmatrix} 0.0012 + 0.06i & -0.01 + 0.0003i & 0 \\ 0.01 - 0.0003i & 0.0012 + 0.06i & 0 \\ 0 & 0 & 0.001 + 0.04i \end{bmatrix},$$

$$[\xi_{r,4}] = \begin{bmatrix} -0.0012 - 0.06i & 0.01 - 0.0003i & 0 \\ -0.01 + 0.0003i & -0.0012 - 0.06i & 0 \\ 0 & 0 & -0.001 - 0.04i \end{bmatrix}$$

To begin the material creation process, click the **User-Defined Material** tab in the **MaterialLibrary** window.

1. **Material IDs 0~4** are pre-configured for Tutorial 1 as shown in Figure 8. However to practice material design in E2M-Win, we will manually create these four materials.

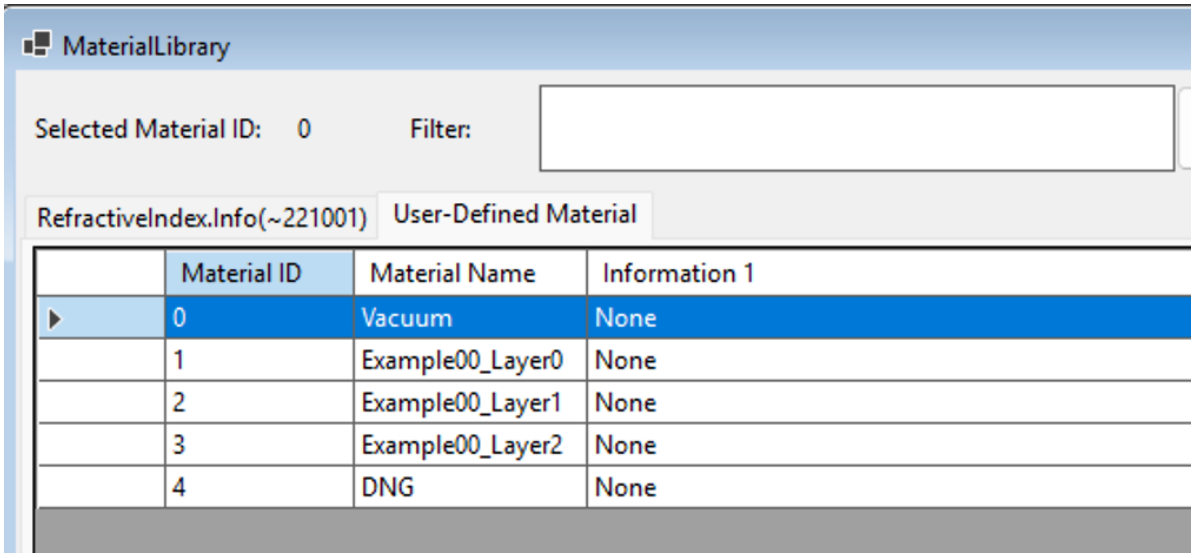

Figure 8. Initial state of the table of MaterialLibrary window

2. Click the **Create a new user-defined material** button.

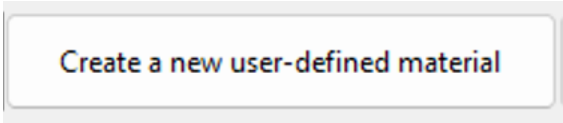

Figure 9. "Create a new user-defined material" button on MaterialLibrary window

3. The “Creation of User-Defined Material Form” window will appear as shown in Figure 10.

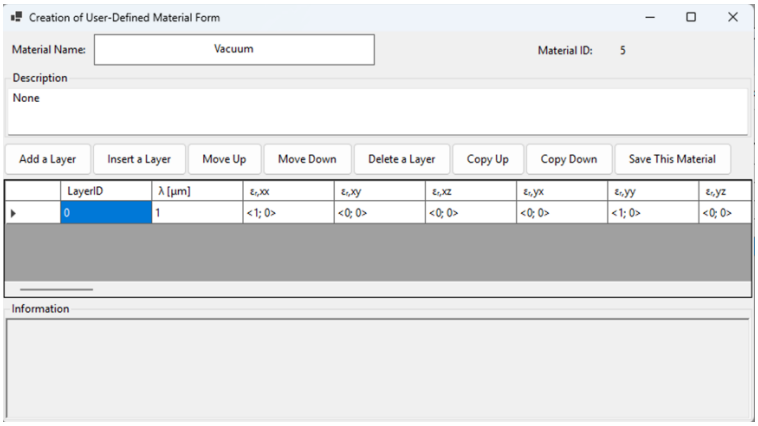

Figure 10. Creation of User-Defined Material From window

4. Click the "**Add a Layer**" button once because this table requires a minimum of two layers ordered by increasing wavelength (λ). After clicking, the row number will be increased as the Figure 11.

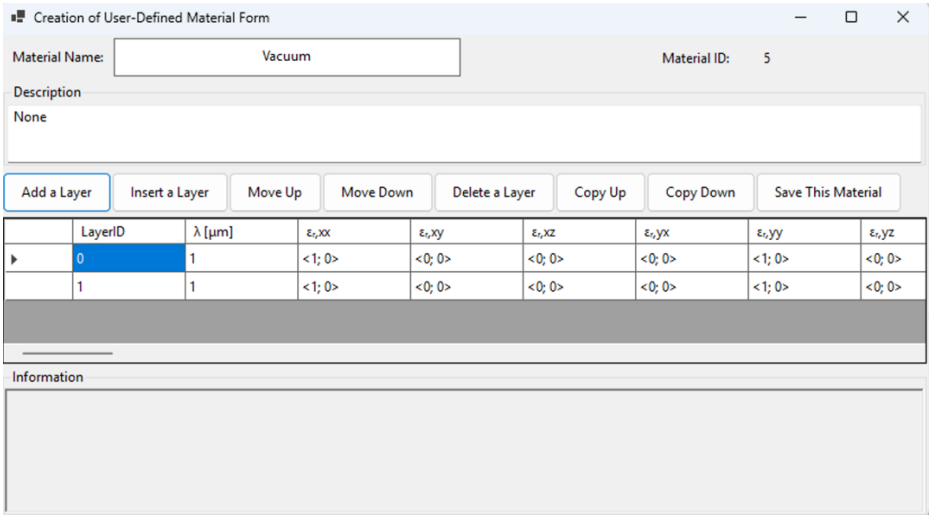

Figure 11. Increased layer number on "Creation of User-Defined Material Form" window after clicking "Add a Layer" button.

5. In the first row (LayerID = 0), click the λ cell, type 0.001, and press **Enter**.
6. In the second row (LayerID = 1), click λ cell, type 10000, and press **Enter**.
7. After sub-steps 5 and 6, the tables will be shown as the Figure 12.

***Note**: The software uses piece-wise linear interpolation for values between the input wavelengths during simulation.*

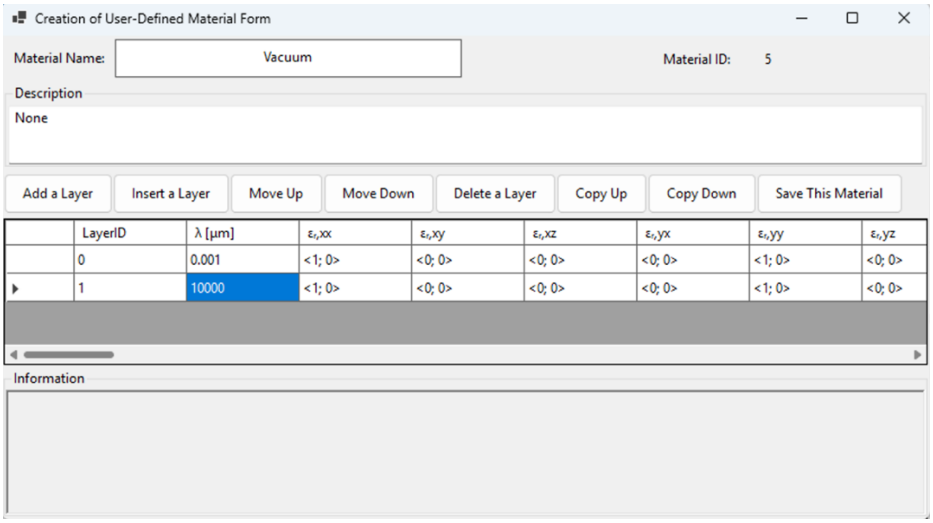

Figure 12. Tables after wavelengths are modified

Inputting Tensor Data: You can scroll horizontally to view all parameter fields, including relative permittivity (ε_r), permeability (μ_r), magneto-electric coupling (ζ_r), and electro-magnetic coupling (ξ_r). The "rot" tensors (e.g., $\varepsilon_{r,rot}$) represent the values after Z-Y-X rotations and are the parameters used during calculation.

Complex numbers should be entered in the format <Real; Imaginary>. While direct cell input is possible, we recommend using the **Matrix Form** for tensor entry.

1. Right-click on a cell in the target λ row to open the context menu as shown in Figure 13.

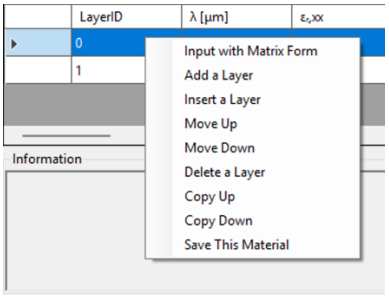

Figure 13. Appeared context menu after right-clicking on a cell

2. Select **Input with Matrix Form**. The "Edit Tensor Properties" window will appear as below.

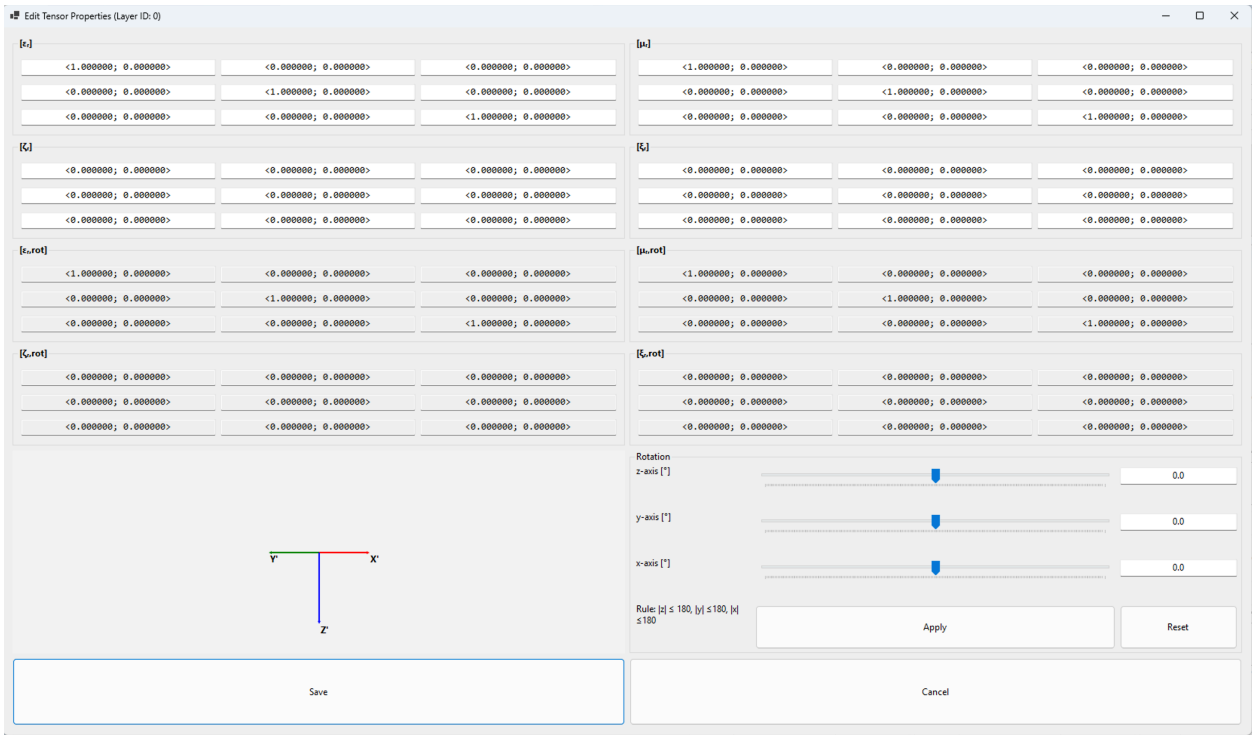

Figure 14. "Edit Tensor Properties" window

3. For **Vacuum** (Material 1), the default identity matrices for ε_r and μ_r (and zero matrices for ζ_r and ξ_r) are already correct. Click **Save** to close the form.
4. Click **Save This Material** to save the "Vacuum" material, then close the window.

Creating Material 2:

Parameters of Material 2 are as below.

$$[\varepsilon_{r,2}] = \begin{bmatrix} 2.9 - 0.04i & 0 & 0 \\ 0 & 2.5 - 0.03i & 0 \\ 0 & 0 & 2.1 - 0.02i \end{bmatrix},$$

$$[\mu_{r,2}] = \begin{bmatrix} 1.1 - 0.025i & 0 & 0 \\ 0 & 1.05 - 0.015i & 0 \\ 0 & 0 & 1.02 - 0.012i \end{bmatrix},$$

$$[\zeta_{r,2}] = \begin{bmatrix} 0.0008 + 0.1i & 0 & 0 \\ 0 & 0.0006 + 0.07i & 0 \\ 0 & 0 & 0.0005 + 0.06i \end{bmatrix},$$

$$[\xi_{r,2}] = \begin{bmatrix} -0.0008 - 0.1i & 0 & 0 \\ 0 & -0.0006 - 0.07i & 0 \\ 0 & 0 & -0.0005 - 0.06i \end{bmatrix}$$

1. Click **Create a new user-defined material** again.
2. Rename the material to "Material 2" in the text box, then the window will be changed as shown in Figure 15.

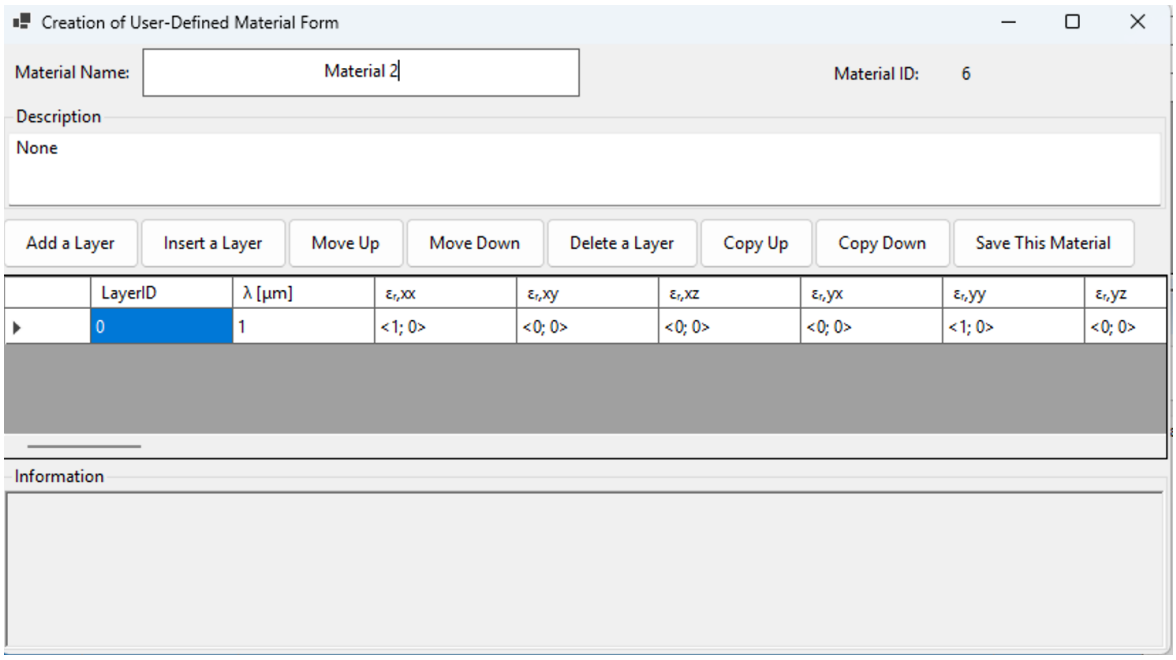

Figure 15. "Creation of User-Defined Material Form" window after renaming the material

3. Right-click the first row and select **Input with Matrix Form**.
4. Input the tensor values as shown in the Figure 16 or the tensor matrices above.

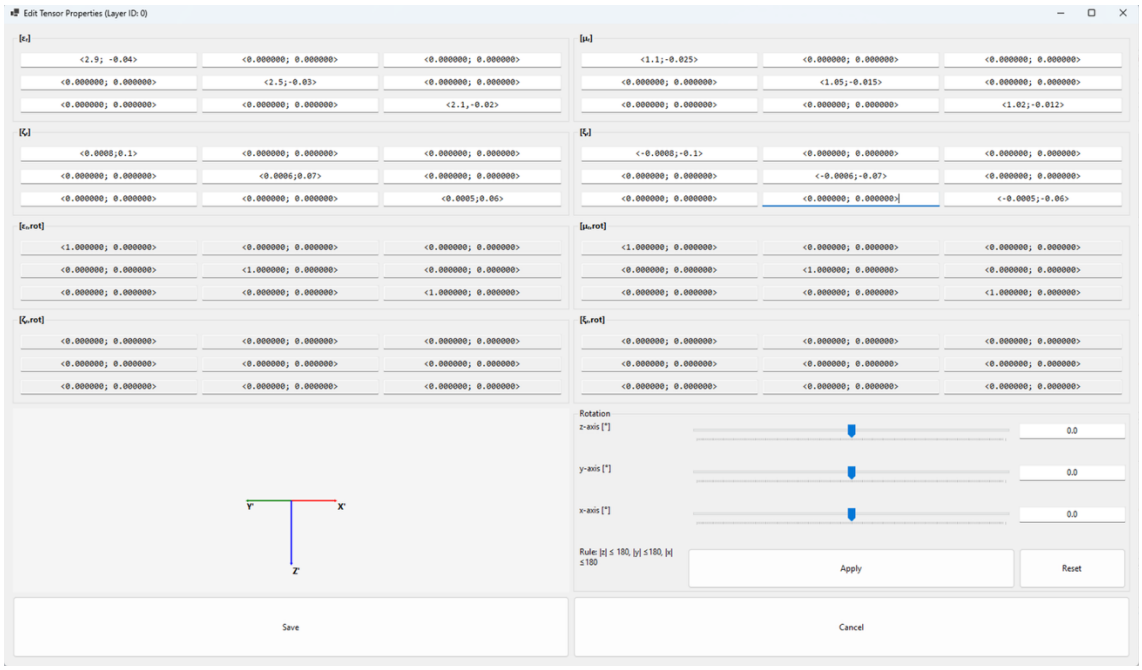

Figure 16. "Edit Tensor Properties" window after typing all parameters of Material 2

Important Note on Sign Convention: The reference text uses a **positive** sign convention, whereas E2M-Win utilizes a **negative** sign convention. Therefore, the imaginary parts of the tensors must be complex conjugated (signs flipped) relative to the reference values.

5. Click **Apply** to confirm zero rotation for the axes. The input tensors will be copied to the rotation tensors.

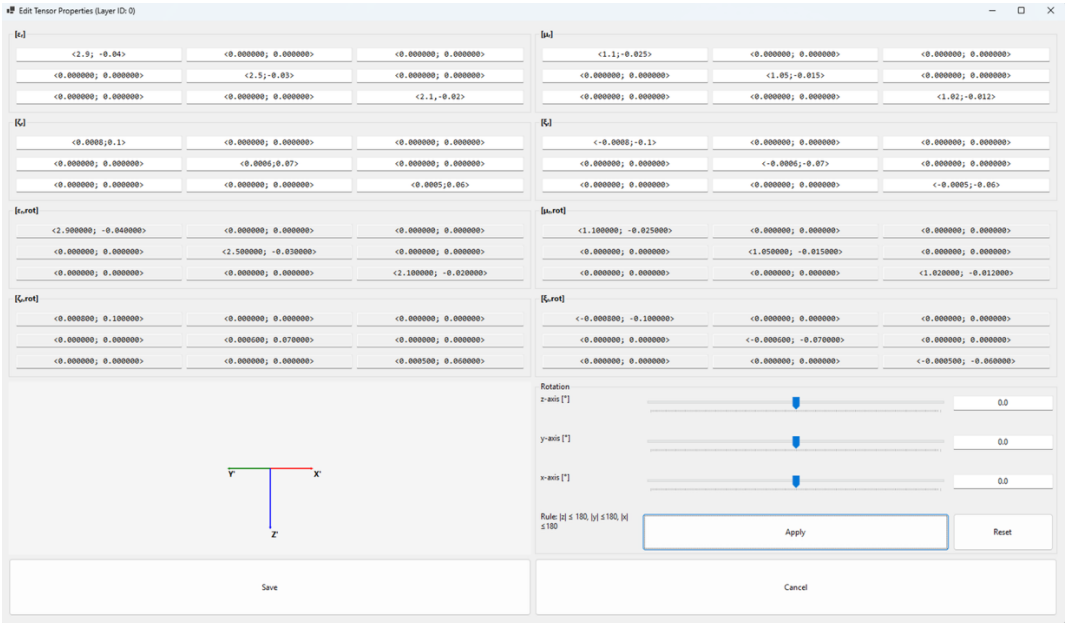

Figure 17. The window after clicking "Apply" button

6. Click **Save** to close the matrix window.

7. Set the λ of the first row as 0.001. Click **Copy Down** to duplicate this data to the second row, then change the second row's λ to 10000. Then, the input is finished as shown in Figure 18.

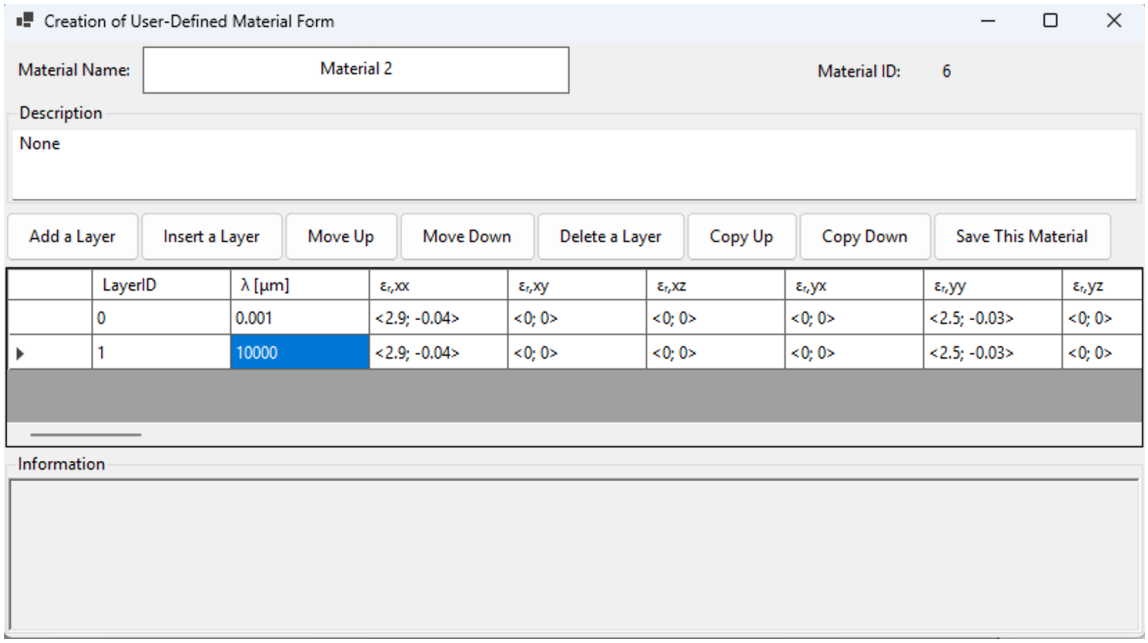

Figure 18. "Creation of User-Defined Material Form" after finishing all input

8. Click Save This Material and close the window.

Creating Material 3 & 4:

1. Select "Material 2" and click **Duplicate** to create a copy at the bottom of the list.
2. Double-click the new row (Material ID = 7) to edit. Rename it to "Material 3" and update the tensor parameters as below.

$$[\varepsilon_{r,3}] = \begin{bmatrix} 2.4 - 0.03i & 0 & 0 \\ 0 & 1.9 - 0.02i & 0 \\ 0 & 0 & 2.4 - 0.03i \end{bmatrix},$$

$$[\mu_{r,3}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, [\zeta_{r,3}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, [\xi_{r,3}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Remember to click 'Apply' in the matrix form before saving.

3. Repeat the process to create "Material 4" (Material ID = 8) with the specified parameters as below.

$$[\varepsilon_{r,4}] = \begin{bmatrix} 4.1 - 0.08i & 0.005 + 0.8i & 0 \\ -0.005 - 0.8i & 4.1 - 0.08i & 0 \\ 0 & 0 & 3.4 - 0.06i \end{bmatrix},$$

$$[\mu_{r,4}] = \begin{bmatrix} 1.3 - 0.04i & 0.003 + 0.35i & 0 \\ -0.003 - 0.35i & 1.3 - 0.04i & 0 \\ 0 & 0 & 1.1 - 0.03i \end{bmatrix},$$

$$[\zeta_{r,4}] = \begin{bmatrix} 0.0012 + 0.06i & -0.01 + 0.0003i & 0 \\ 0.01 - 0.0003i & 0.0012 + 0.06i & 0 \\ 0 & 0 & 0.001 + 0.04i \end{bmatrix},$$

$$[\xi_{r,4}] = \begin{bmatrix} -0.0012 - 0.06i & 0.01 - 0.0003i & 0 \\ -0.01 + 0.0003i & -0.0012 - 0.06i & 0 \\ 0 & 0 & -0.001 - 0.04i \end{bmatrix}.$$

Once finished, you can verify the input tensor graphs on the right side of the **MaterialLibrary** window as the Figure 19 below.

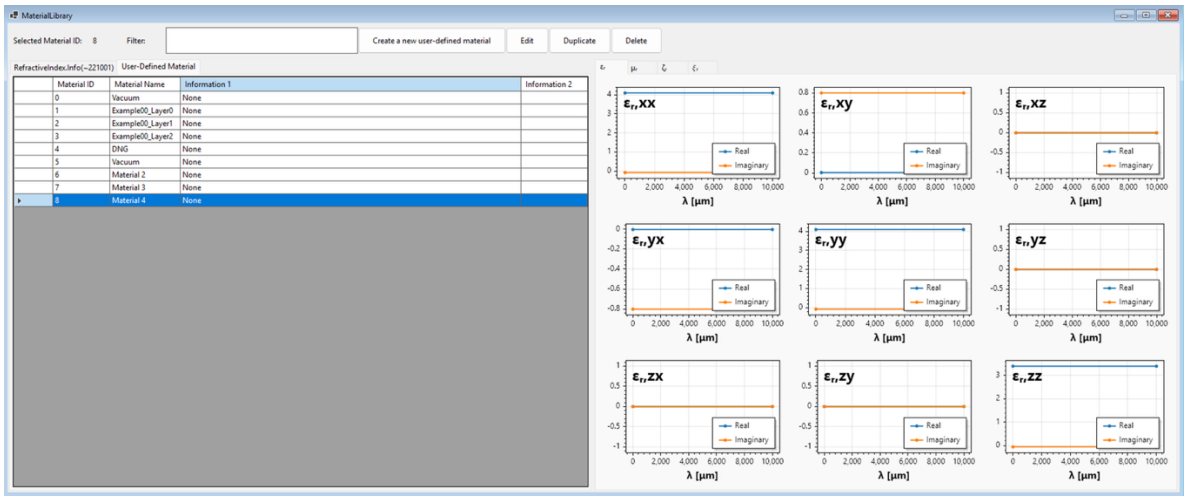

Figure 19. MaterialLibrary table rows and graphs after preparation steps are finished

[Step3: Design Layers]

1. The **Layer Designer** allows you to configure the structure. Modify each cell with the parameters of the following Table 1.

Table 1. Parameters to be filled in the Layer Designer's table

Layer Index	Material ID	Material Name	Information	Thickness [μm]	User-Defined Data	Group Index	Repetition Number of Group
0	5	Vacuum	None	1	True	0	1
1	6	Material 2	None	0.504	True	0	1
2	7	Material 3	None	1.008	True	0	1
3	8	Material 4	None	0.672	True	0	1
4	5	Vacuum	None	1	True	0	1

2. Ensure the **User-Defined Data** checkbox is **checked** for all layers to use the materials you just created. After sub-steps 1 and 2 are completed, the “Layer Designer” window will be as shown in Figure 20.

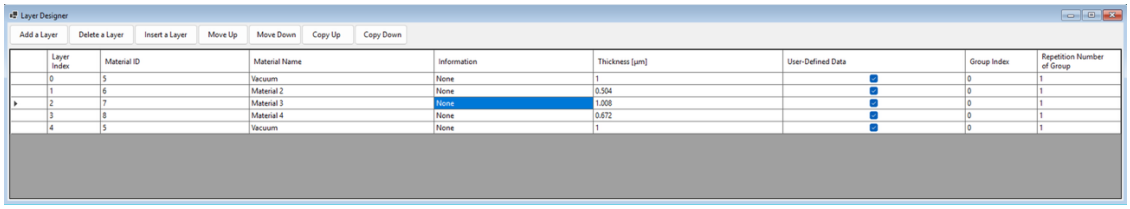

Figure 20. Layer Designer window after all parameters are set up correctly

Note: If **User-Defined Data** is unchecked, the ‘Material ID’ refers to the default refractive index database (isotropic and non-magnetic assumptions are applied for this database in E2M-Win currently.)

3. (Optional) You can use the **Add a Layer**, **Delete a Layer**, **Insert a Layer**, **Move Up**, **Move Down**, **Copy Up**, and **Copy Down** buttons to modify the layer structure. Each button functions as its name suggests. Right-clicking a cell reveals a context menu with the same options and their corresponding shortcut keys.

[Step4: Simulation & Results]

1. Click the **Simulation** icon on the left (or press 'Ctrl+R') to open 'Simulation Condition' window. Then, input the following parameters:
    a. Polarization state for TE: <1;0>
    b. Polarization state for TM: <0;0>
    c. θ: 0°~90° ($\Delta\theta$: 2.5°)
    d. ϕ: 0°~180° ($\Delta\phi$: 5°)
    e. λ: 0.56~0.66 μm ($\Delta\lambda$: 0.01 μm)

    After that, click **Apply**. Then, the 'Simulation Condition' window is shown like Figure 21 below.

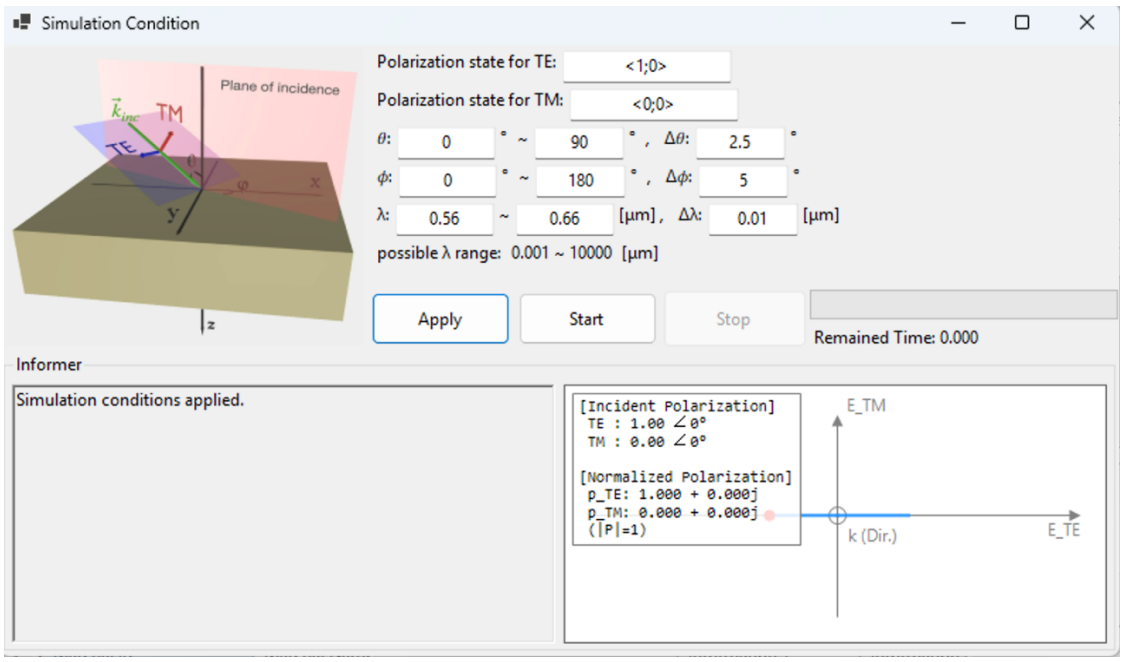

Figure 21. "Simulation Condition" window after the setup for recalculation is finished.

The possible λ range will be calculated automatically. Bottom-right side figure shows the current state of incident polarization. Since we selected TE mode only, the polarization graph shows horizontal line on E_TE axis. E_TE means electric field with TE mode.
Click **Start** to run the simulation.

2. After the simulation is complete, the result windows will appear as shown in Figure 22. Titles of all windows are 'Reflectance', 'Transmittance', 'Absorptance', 'Rs', 'Rp', 'Ts', and 'Tp', respectively.

    Notation: Subscript 's' denotes s-polarized (TE) and 'p' denotes p-polarized (TM). Since we set up TE mode in this tutorial, by following scientific convention, 'Rs', 'Rp', 'Ts', and 'Tp' are

identical to ‘Rss’, ‘Rps’, ‘Tss’, and ‘Tps’, respectively. If we set up TM mode only in simulation condition window, ‘Rs’, ‘Rp’, ‘Ts’, and ‘Tp’ will be identical to ‘Rsp’, ‘Rpp’, ‘Tsp’, and ‘Tpp’, respectively. Here, ‘Reflectance’, ‘Transmittance’, and ‘Absorptance refer to ‘Rs + Rp’, ‘Ts + Tp’, and ‘As + Ap’, respectively.

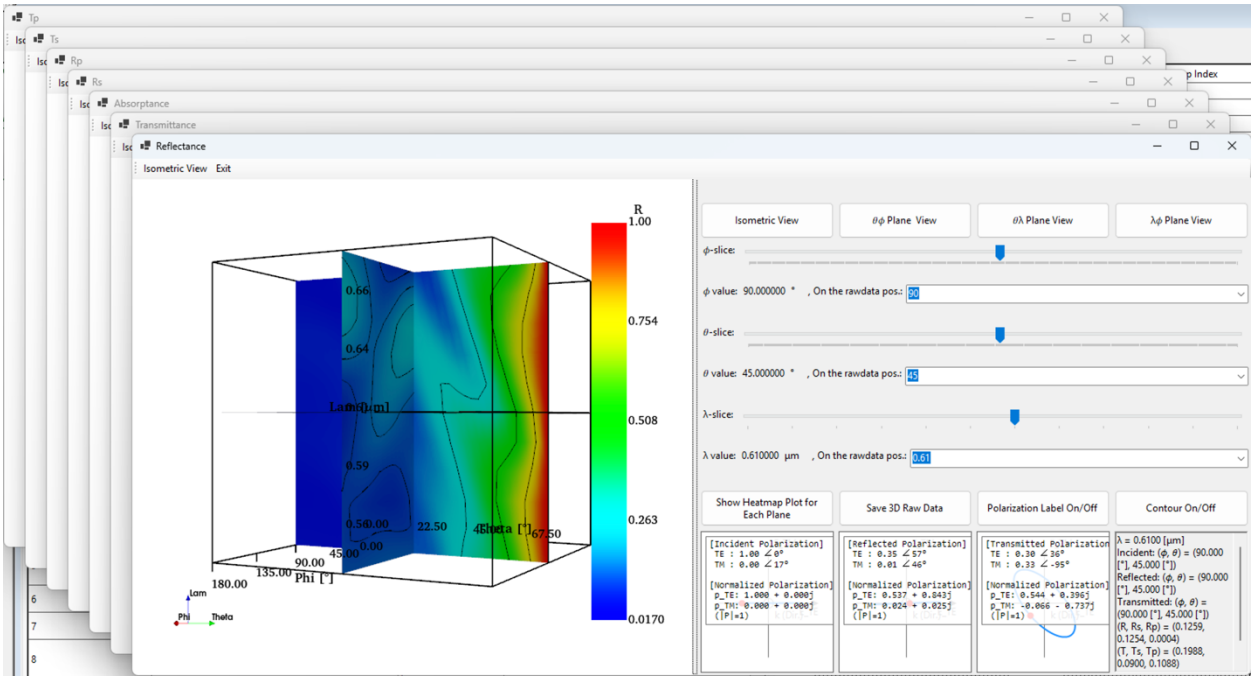

Figure 22. Windows showing visualized results related to each title

3. Let’s select the ‘Rs’ window for this step as below.
   Here, each button has the functionality of the Table 2.

Table 2. Button names and those functionality on result windows

Button Name	Functionality
Isometric View	The three coordinate axes appear equally foreshortened and the angle between any two of them is 120 degrees.
$\theta\phi$ Plane View	Shows $\theta\phi$ plane by adjusting 3D graph.
$\theta\lambda$ Plane View	Shows $\theta\lambda$ plane by adjusting 3D graph.
$\lambda\phi$ Plane View	Shows $\lambda\phi$ plane by adjusting 3D graph.
Show Heatmap Plot for Each Plane	Show heatmap plot for three selected planes.
Save 3D Raw Data	Save all calculated data. Saved parameters are ϕ_{inc}, ϕ_{ref}, ϕ_{trn}, θ_{inc}, θ_{ref}, θ_{trn}, λ_{inc}, λ_{ref}, λ_{trn}, R, Rs, Rp, T, Ts, Tp, A, $E_{inc,x}$, $E_{inc,y}$, $E_{inc,z}$, $E_{ref,x}$, $E_{ref,y}$, $E_{ref,z}$, $E_{trn,x}$, $E_{trn,y}$, and $E_{trn,z}$. Here, ‘inc’, ‘ref’, and ‘trn’ mean incidence, reflectance, and transmittance, respectively. Also, E means frequency domain normalized electric field.
Polarization Label On/Off	Toggle labels of polarization graphs.
Contour On/Off	Toggle contour lines on 3D graph.

Users can move the positions of cutting planes by scrolling mouse wheels or selecting combo boxes. Turn off polarization labels and select $\phi = 90°$, $\theta = 45°$, and $\lambda = 0.56\ [\mu m]$ as shown in the figure below. Users can observe that the reflected polarization and transmitted polarization graphs are changed as the different values on combo boxes are selected.

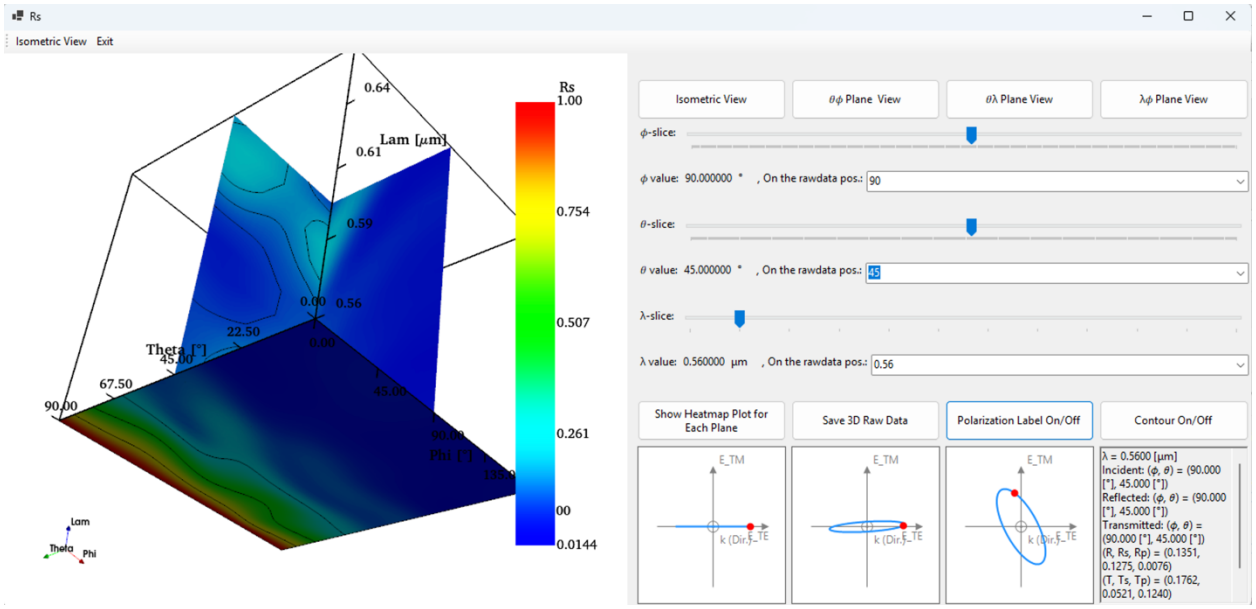

Figure 23. Rs window after $\phi = 90°$, $\theta = 45°$, and $\lambda = 0.56\ [\mu m]$ are selected on each combo boxes.

As the next step, click 'Show Heatmap Plot for Each Plane' button. Then, three figures related to each plane are created as shown in Figure 24 ~ 26.

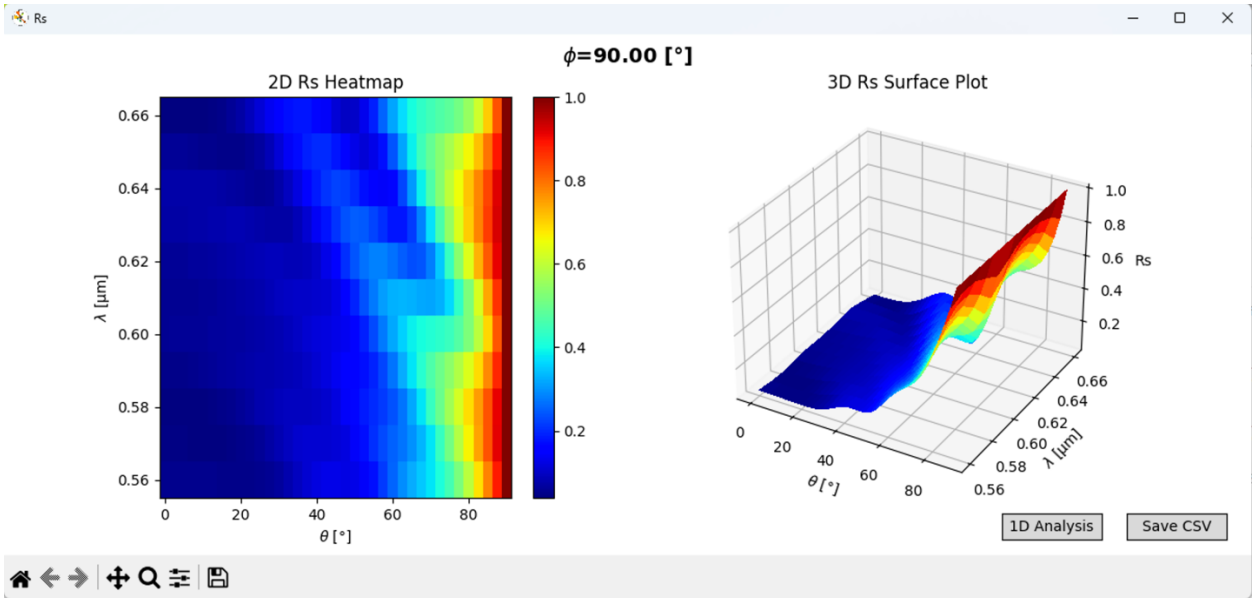

Figure 24. Heatmap plot at the cutting plane $\phi = 90°$

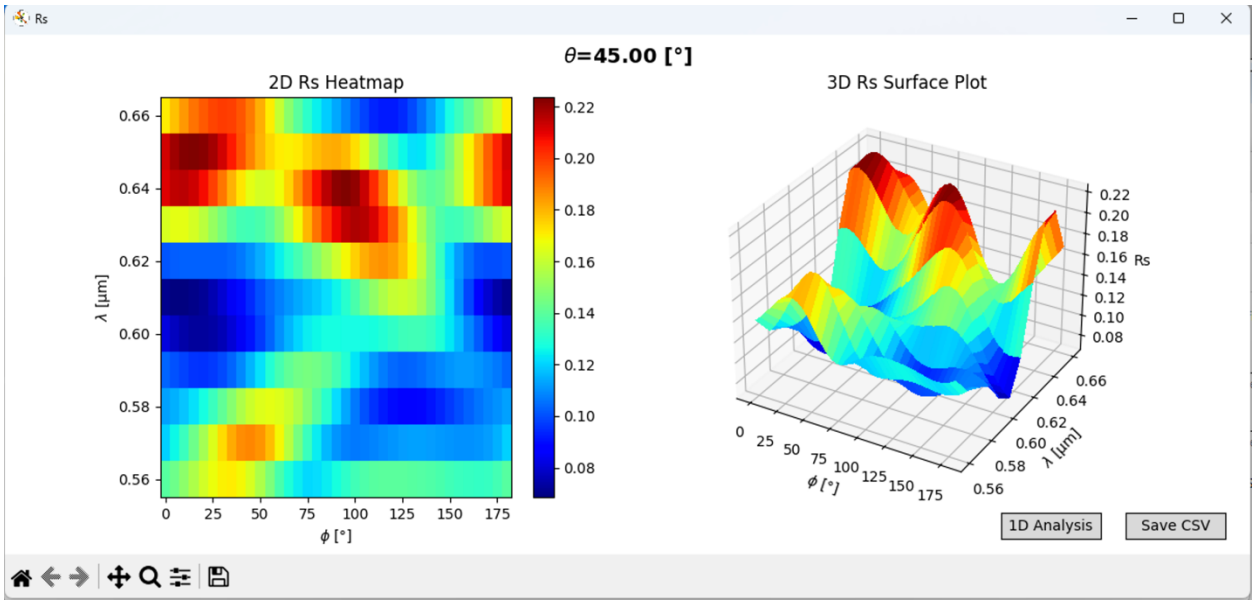

Figure 25. Heatmap plot at the cutting plane $\theta = 45°$

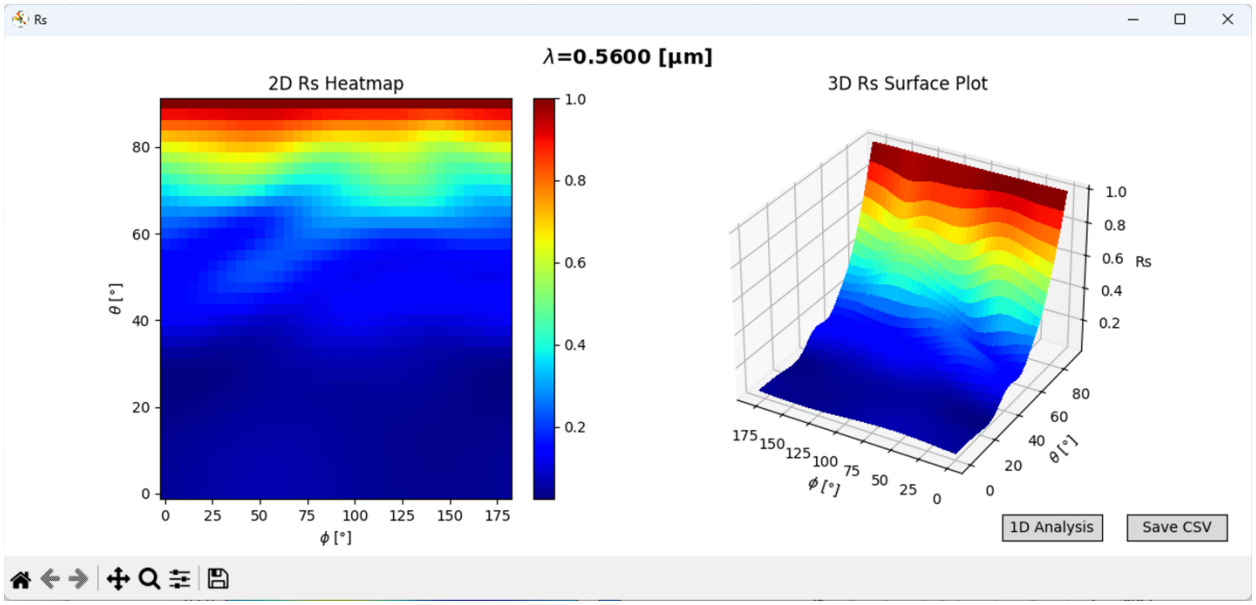

Figure 26. Heatmap plot at the cutting plane $\lambda = 0.56\ [\mu m]$

Here, plots for $\lambda = 0.56\ [\mu m]$ is related to our target reference. Users can hover the mouse cursors on heatmap and surface plots to see data value. Users can save these plane data as a

csv file by clicking ‘Save CSV’ button. Clicking ‘1D Analysis’ button of $\lambda = 0.56\ [\mu m]$ shows ‘Line Profile’ window as shown in Figure 27 below.

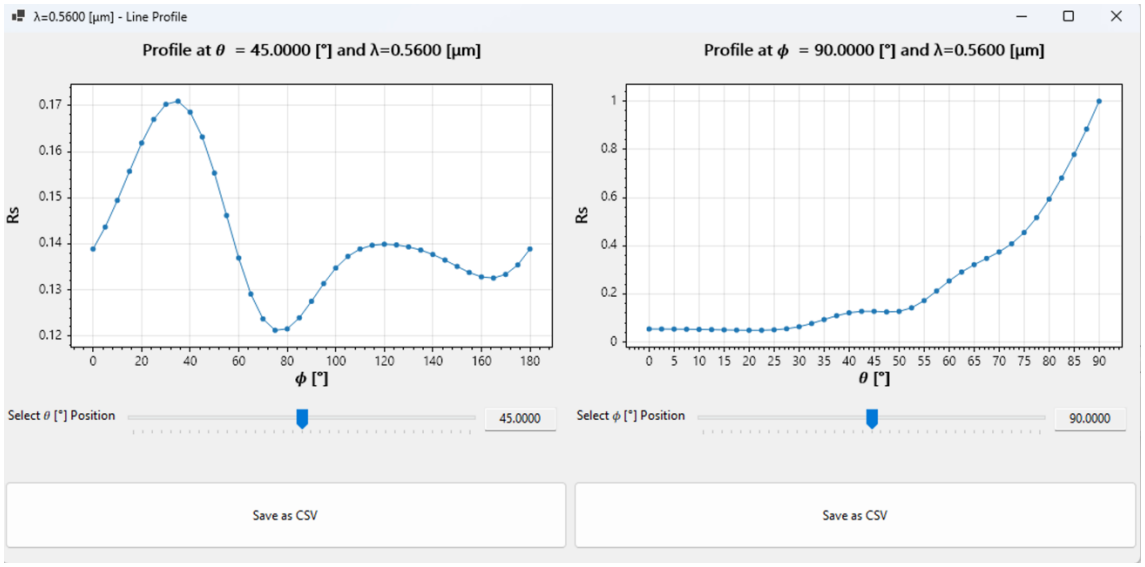

Figure 27. Line Profile window for a selected plane

By utilizing sliders, line profiles at selected cutlines can be visualized. If user wants to extract the selected line profiles, click ‘Save as CSV’ button.

4. For Rp, Ts, Tp, and A, identical steps like above can be used to observe the Figure 1 of page 3.

[Comparison: Error Rate between the Reference and Tutorial 1 of E2M-Win]

Users can extract raw data by clicking the "**Save 3D Raw Data**" button in E2M-Win. We provide the comparison raw data on our webpage at the link below.

Link: https://www.comphysics.com/index.php/e2m-win

According to our comparison, the maximum difference between the reference and the simulation results was 6.41×10^{-13} for all R, T, and A spectra.