Model created in COMSOL Multiphysics 6.4

Reflection of a Circularly Polarized Plane Wave

Introduction

A circularly polarized plane wave is reflected and transmitted at a boundary between air and a dielectric material. This model demonstrates how to solve this problem using three different approaches:

- with ports and user-defined mode fields
- with ports, selecting the proper circular polarizations for the mode fields
- with a *Periodic structure* feature, specifying the circular polarization for the incident wave

This example demonstrates that the simplest way to correctly model this problem is to use the *Periodic Structure* feature.

Starting from the theoretical framework described in the Fresnel Equations model, comparisons show excellent agreement between the computed results and analytical expressions for the polarization state of the reflected and transmitted waves.

A plane wave propagating in an isotropic homogeneous material can have a polarization state that is the superposition of two orthogonal polarization base states. The simplest polarization base states are linear polarization states. Here, the electric field vector oscillates in a plane that is constant along the propagation direction.

As in this case, the incident wave is reflected and refracted at an interface between two different materials, it is common to define the two orthogonal polarization states as the out-of-plane s- or TE-polarization and the in-plane p- or TM-polarization. The s-polarization is directed in the out-of-plane direction with respect to the plane of incidence, defined by the propagation direction and the normal to the interface plane. The p-polarization is pointing in a direction parallel to the plane of incidence.

If you add s- and p-polarizations with equal amplitudes and with a $\pi/2$ phase shift, you get circular polarization. If you monitor the electric field amplitude vector at a point in space as a function of time, the amplitude vector tip will rotate along a circle. Thereby the name, circular polarization. For right-handed circular polarization (RHCP), if you align the thumb of the right hand in the propagation direction, away from the source, the other fingers align in the direction the amplitude vector rotates as a function of time. Similarly, for left-handed circular polarization (LHCP), you align the left hand thumb in the propagation direction and the amplitude vector rotates as a function of time in the direction of the other fingers on the left hand.

Model Definition

An incident plane wave with pure RHCP propagates through air (n_air = 1). At the interface between air and the dielectric (n_slab = 1.5), the wave is split into a reflected wave and a transmitted (refracted) wave (see Figure 1).

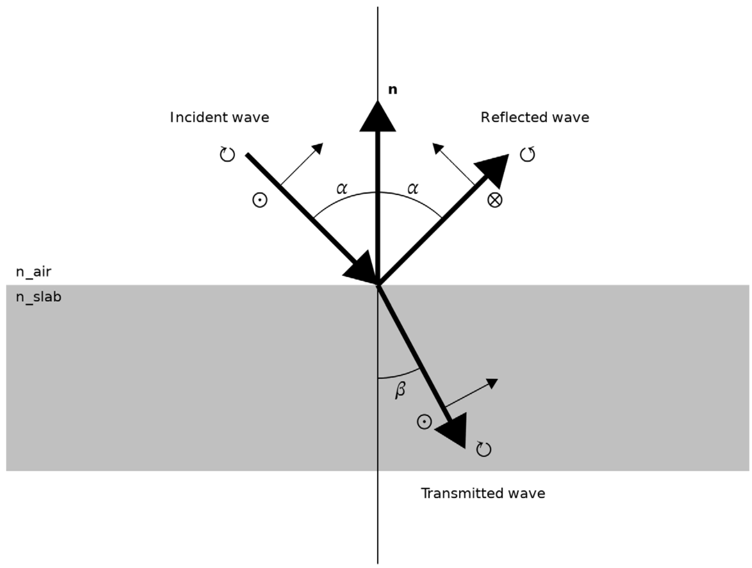


Figure 1: The incident and reflected waves propagate in air, whereas the transmitted wave propagates in an infinitely thick dielectric medium. The incident wave has pure right-handed circular polarization (RHCP), whereas the reflected wave has a mix of left-handed circular polarization (LHCP) and some RHCP. The transmitted wave has mostly RHCP, but also some LHCP. The rings with crosses or dots represent s-polarization directions into or out from the page and the short in-plane arrows represent p-polarization directions for the respective waves. The rings with a small arrow represent the circular polarization state, watching the polarization vector rotate as a function of time when looking in the propagation direction of the respective waves.

Circular polarization consists of equal amplitudes of s- and p-polarization. However, for non-normal angles of incidence, the reflection and transmission coefficients for s- and p-polarizations are different. This is described in more detail in the Fresnel Equations model. The effect is that the reflected and transmitted waves don’t contain a single circular polarization state, but a mix of RCHP and LHCP.

The transmitted wave consists of mostly RHCP, but also some LHCP.

The amplitude vector for the reflected wave rotates in the same direction as the amplitude vector of the incident wave. However, since the propagation directions are different, the reflected wave consists mostly of LCHP, but with some RHCP. The amount of LHCP and RHCP depends on the angle of incidence.

At the Brewster angle, the reflection coefficient for p-polarization is zero. Thus, at that angle, the reflected wave is purely s-polarized. Another way of describing the polarization at the Brewster angle is to say that the reflected wave consists of equal amounts of RHCP and LHCP and that the superposition of those two circular polarization states generates a pure s-polarization.

Mathematically, the incident wave can be described by the summation of equal amplitudes of s- and p-polarization,

$$\mathbf{E}_{\text{in}} = \frac{E_0}{\sqrt{2}}(\mathbf{u}_s + j\mathbf{u}_p)\exp(-j(\mathbf{k}_{\text{in}} \cdot \mathbf{r})) = E_0\mathbf{u}_R\exp(-j(\mathbf{k}_{\text{in}} \cdot \mathbf{r})), \tag{1}$$

where E_0 is the amplitude; $\mathbf{u}_s$, $\mathbf{u}_p$, and $\mathbf{u}_R$ are the polarization directions for s-, p-, and right-handed circular polarization, respectively; $\mathbf{k}_{\text{in}}$ is the wave vector for the incident wave; and $\mathbf{r}$ is the position vector. Note that the RHCP direction is formed by adding the s- and p-polarization directions with the $\pi/2$ phase difference (the factor j).

The polarization direction for LHCP is given by

$$\mathbf{u}_L = \frac{1}{\sqrt{2}}(\mathbf{u}_s - j\mathbf{u}_p). \tag{2}$$

Using the Fresnel reflection coefficients, defined and discussed in the Fresnel Equations model, the reflected wave is written as

$$\mathbf{E}_{\text{r}} = \frac{E_0}{\sqrt{2}}(r_s\mathbf{u}_s + jr_p\mathbf{u}_p)\exp(-j(\mathbf{k}_r \cdot \mathbf{r})) = E_0(r_R\mathbf{u}_R + r_L\mathbf{u}_L)\exp(-j(\mathbf{k}_{\text{r}} \cdot \mathbf{r})). \tag{3}$$

Identifying the coefficients belonging to the respective s- and p-polarization vectors, the following two relations can be derived for the reflection coefficients

$$r_s = r_R + r_L \tag{4}$$

and

$$r_p = r_R - r_L. \tag{5}$$

From these equations, the reflection coefficients for the circular polarizations can be deduced as

$$r_R = (r_s + r_p)/2 \tag{6}$$

and

$$r_L = (r_s - r_p)/2 . \tag{7}$$

Since the dielectric has a larger refractive index than air, the reflection coefficient for s-polarization, r_s, is negative, whereas the reflection coefficient for p-polarization is positive for small angles of incidence. Thereby, for small angles of incidence, the reflection coefficient for LHCP will be larger than the reflection coefficient for RHCP. However, for angles of incidence larger than the Brewster angle, also the reflection coefficient for p-polarization, r_p, is negative. Then the reflection coefficient for RHCP will be larger than the reflection coefficient for LHCP.

In COMSOL, the mode fields are specified for the outgoing waves — both for the excitation port and the ports without excitation. Because of the different propagation directions for the incoming and the outgoing waves, the same mode fields represents different polarization states for the incoming and the outgoing waves. Thus, to specify an incoming waves with RHCP, you should specify a mode field for the outgoing wave with LHCP. Furthermore, as circular polarization can be decomposed into a superposition of s- and p-polarizations and the reflection and transmission coefficients are different for the two polarizations for non-normal incidence, at each port boundary both a *Port* node and an *Orthogonal Polarization* node must be added to handle the fact that the reflection/transmission coefficients are different for the two polarizations.

This model describes three different ways to solve this problem. First, *Port* nodes with user-defined electric mode field amplitudes are used. Now, it is important to define the components of the LHCP for the excitation port and RHCP for the listener port.

S-polarization means that the electric field vector is orthogonal to the plane of incidence, which is spanned by the normal to the interface between the two media and the propagation direction. Thus, we can define the s-polarization vector as

$$\mathbf{u}_s = \frac{\mathbf{k} \times \mathbf{n}}{|\mathbf{k} \times \mathbf{n}|} = \frac{\mathbf{k}_T \times \mathbf{n}}{|\mathbf{k}_T \times \mathbf{n}|} = \mp\mathbf{y} \tag{8}$$

where $\mathbf{k}$ is the wave vector for any of the incident, reflected, or transmitted waves, $\mathbf{k}_T$ is the component of the wave vector that is tangential to the port boundary (pointing in the x-direction and the same for all the waves), $\mathbf{n}$ is the port normal (pointing out from the physics) and $\mathbf{y}$ is the unit vector in the y-direction. The minus sign is used for the excitation port, as there $\mathbf{n} = \mathbf{z}$, whereas the plus sign is used on the opposite port boundary, as there $\mathbf{n} = -\mathbf{z}$.

The p-polarization vector should be orthogonal to both the s-polarization vector and the propagation direction. Thus, it can be defined as

$$\mathbf{u}_p = \frac{\mathbf{u}_s \times \mathbf{k}}{|\mathbf{u}_s \times \mathbf{k}|} = \begin{cases} -\cos\alpha\mathbf{x} + \sin\alpha\mathbf{z} & \text{Port 1} \\ -\cos\beta\mathbf{x} - \sin\beta\mathbf{z} & \text{Port 2} \end{cases} \tag{9}$$

So, for Port 1, the excitation port, a mode field amplitude representing LHCP is defined by

$$\mathbf{u}_L = \mathbf{u}_s - j\mathbf{u}_p = -\mathbf{y} - j(-\cos\alpha\mathbf{x} + \sin\alpha\mathbf{z}) = j\cos\alpha\mathbf{x} - \mathbf{y} - j\sin\alpha\mathbf{z}\,. \tag{10}$$

Similarly, for Port 2, the listener port, a mode field amplitude representing RHCP is defined as

$$\mathbf{u}_R = \mathbf{u}_s + j\mathbf{u}_p = \mathbf{y} + j(-\cos\beta\mathbf{x} - \sin\beta\mathbf{z}) = -j\cos\beta\mathbf{x} + \mathbf{y} - j\sin\beta\mathbf{z}\,. \tag{11}$$

The second approach to model this problem is to specify what kind of circular polarization that will be used by the two ports. The advantage is of course that the electric field amplitude components are automatically defined. However, also in this case it is important to realize that it is the polarization state for the outgoing wave that is specified. Thus, specify LHCP and RHCP for ports 1 and 2, respectively.

The third and final approach to model this problem is to use the *Periodic Structure* node. This is a domain feature that automatically adds all required subnodes, like ports and periodic boundary conditions. Here, it is the polarization of the incident — or dominant — polarization that is specified. Based on this specification, the polarization states for the port subnodes are automatically assigned.

It is highly recommended to use the *Periodic Structure* node when defining periodic problems, as it automatically defines the proper settings for the ports and the periodic conditions. The first two, more manual, approaches, however, are good for getting a more detailed understanding of how the ports are configured to solve the problem correctly.

Results and Discussion

Figure 2 shows the Cartesian components of the electric field distributions, as calculated with the three different modeling approaches. It is clear that all three approaches result in very similar solutions.

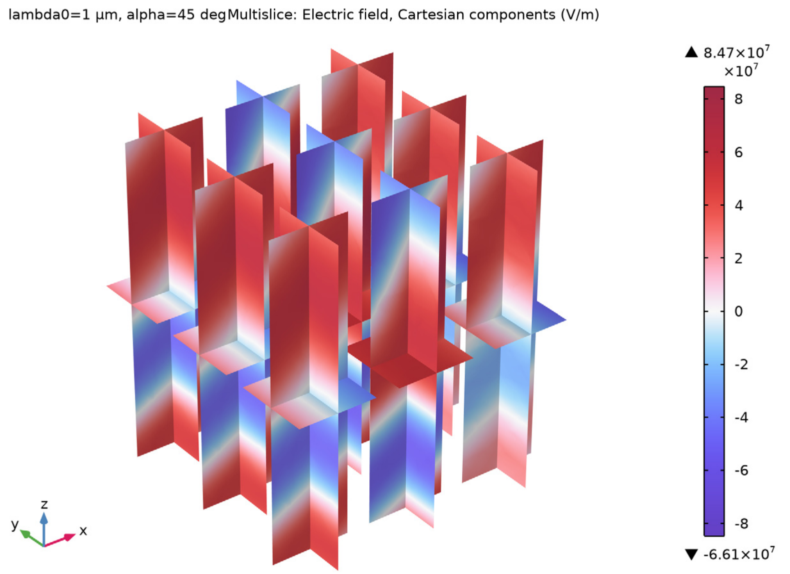


Figure 2: Plot of the Cartesian components of the electric fields for the three different modeling approaches. The different plots along the x-direction show the electric field distributions for the different Cartesian components, whereas the plots along the y-direction show the results for the different modeling approaches.

Figure 3 shows the reflectance and transmittance for the different circular polarization states. For small angles of incidence, the reflectance for LHCP is larger than the reflectance for RHCP. At the Brewster angle, the reflectances for the two circular polarization states are equally large, forming a pure s-polarization for the reflected wave. For angles larger than the Brewster angle, the reflectance for RHCP is larger than the reflectance for LHCP.

The markers represent the analytical solutions, based on Equation 6 and Equation 7. As expected, the analytical values and the results from the full-wave solutions agree very well.

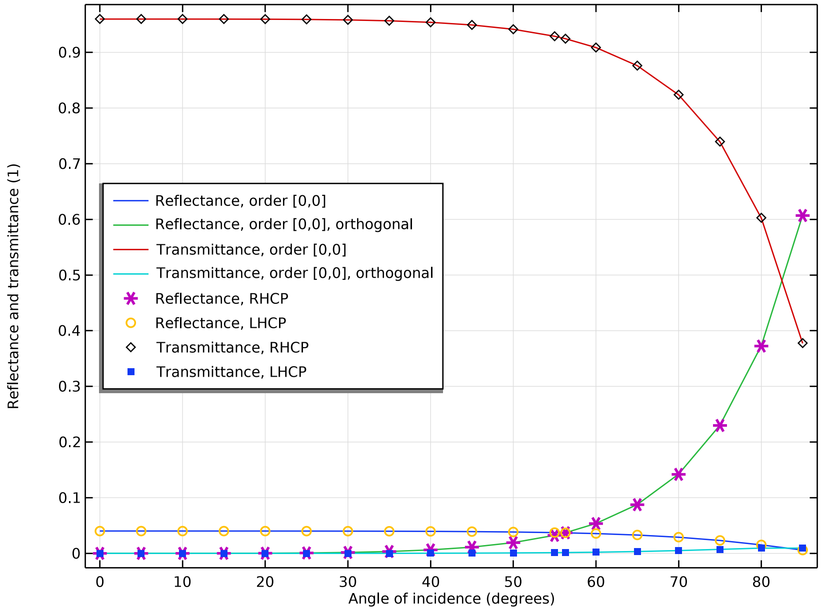


Figure 3: Reflectance and transmittance curves for the different circular polarization states.

Figure 4 shows the polarization plot at the Brewster angle. It is clear that the reflected wave has a pure out-of-plane (s) polarization.

To understand what kind of circular polarization that is shown in the plot, point the right hand thumb into the page (screen). As the rest of the right-hand fingers align with the arrows in the plots for the input and transmitted waves, the input wave is purely RHCP and the transmitted wave is mostly RHCP. For an LHCP wave, the left hand fingers align with the arrow, when the thumb points into the page.

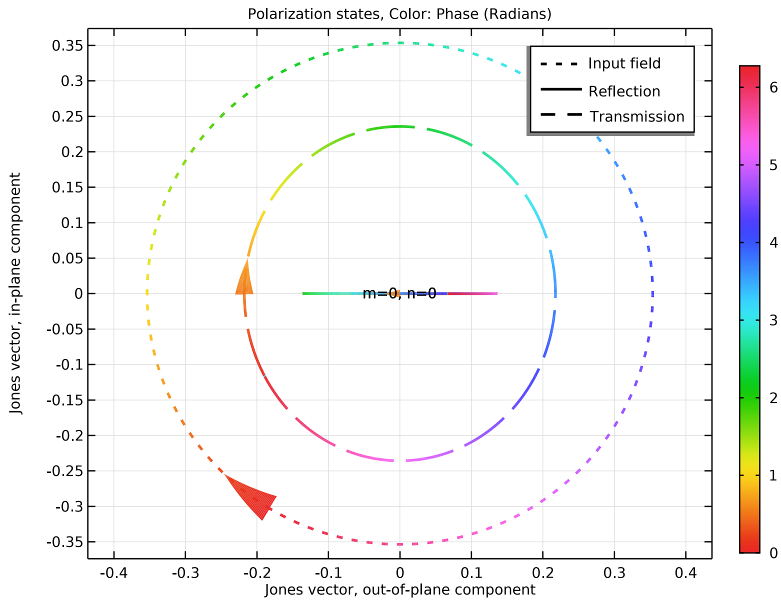


Figure 4: Plot of the polarization states for the input (dotted line), reflected (solid line), and transmitted (dashed line) waves at the Brewster angle.

Application Library path: `Wave_Optics_Module/Verification_Examples/circular_polarization`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **3D**.

2 In the **Select Physics** tree, select **Optics** > **Wave Optics** > **Electromagnetic Waves, Frequency Domain (ewfd)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Wavelength Domain**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `circular_polarization_parameters.txt`.

GEOMETRY 1

Block 1 (blk1)

1 In the **Geometry** toolbar, click **Block**.

2 In the **Settings** window for **Block**, locate the **Size and Shape** section.

3 In the **Width** text field, type `a0`.

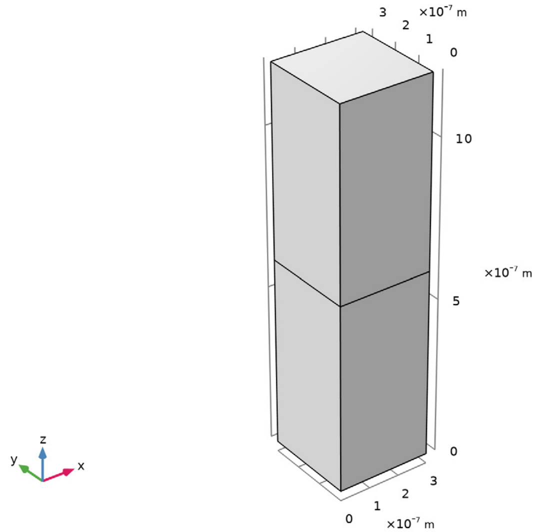
4 In the **Depth** text field, type `a0`.

5 In the **Height** text field, type `b0`.

6 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	b0/2

7 Click **Build All Objects**.



This creates a rectangular geometry, consisting of two layers. The top domain consists of air and the bottom domain consists of glass.

MATERIALS

Air

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Air` in the **Label** text field.

3 Locate the **Material Contents** section. In the table, enter the following settings:

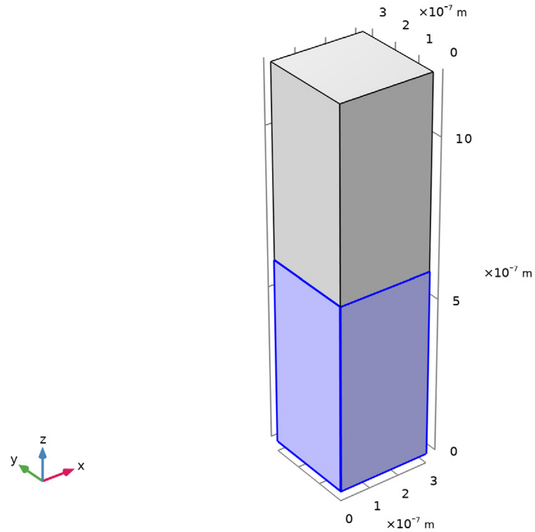
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_air`	1	Refractive index

Glass

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Glass` in the **Label** text field.

3 Select Domain 1 only.



4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	n_slab	1	Refractive index

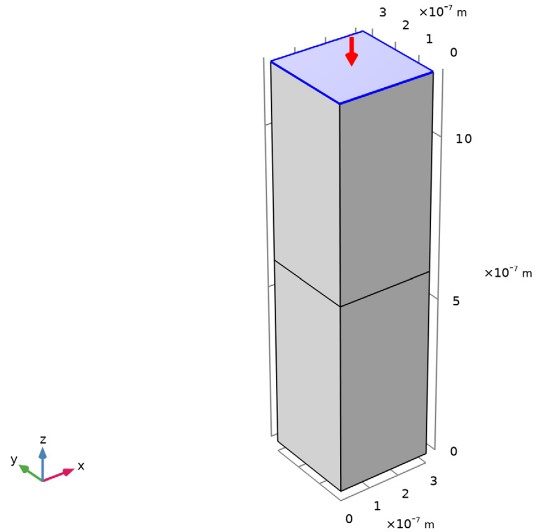
ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Now, define the first physics interface. Here, periodic **Port** features will be used, with user-defined settings for the port mode field amplitudes.

Port 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 Select Boundary 7 only.



3 In the **Settings** window for **Port**, locate the **Boundary Selection** section.

4 Click **Create Selection**, as this selection will be reused later.

5 In the **Create Selection** dialog, type `Port 1` in the **Selection name** text field.

6 Click **OK**.

7 In the **Settings** window for **Port**, locate the **Port Properties** section.

8 From the **Type of port** list, choose **Periodic**.

9 Locate the **Port Mode Settings** section. Specify the $\mathbf{E}_0$ vector as

`i*cos(alpha)`	x
`-1`	y
`-i*sin(alpha)`	z

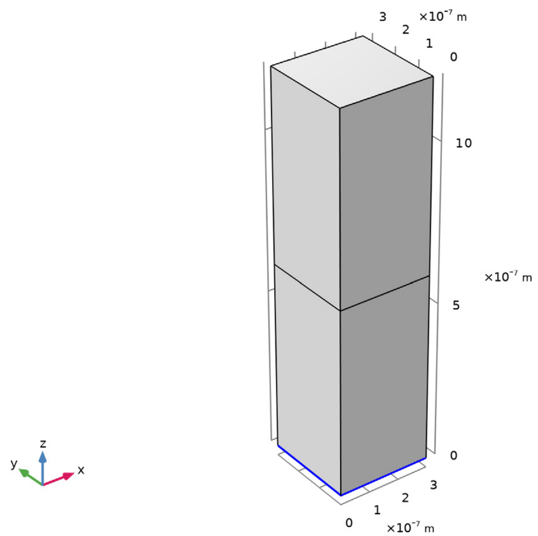
These settings create a mode field amplitude that is orthogonal to the wave vector for the *outgoing* wave. The s-polarization (TE) is defined by the y component and the x and z components define the p-polarization (TM). Because the amplitudes for the s- and p-polarizations are of equal magnitude and there is a $\pi/2$ phase shift between the two linear polarizations, these settings will define a left-handed circular polarization for the *outgoing* wave. That means the incident wave will have right-handed circular polarization.

10 In the α_1 text field, type `alpha`.

Port 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 Select Boundary 3 only.



3 In the **Settings** window for **Port**, locate the **Boundary Selection** section.

4 Click **Create Selection**.

5 In the **Create Selection** dialog, type `Port 2` in the **Selection name** text field.

6 Click **OK**.

7 In the **Settings** window for **Port**, locate the **Port Properties** section.

8 From the **Type of port** list, choose **Periodic**.

9 Locate the **Port Mode Settings** section. Specify the $\mathbf{E}_0$ vector as

`-i*cos(beta)`	x
`1`	y
`-i*sin(beta)`	z

These settings define a right-handed circular polarization for the *outgoing* wave at the second port.

Port 1

Now, define **Orthogonal Polarization** ports, as subnodes to the two periodic **Port** nodes. These **Orthogonal Polarization** ports will absorb the radiation that does not match the mode fields of the periodic **Port** nodes.

In the **Model Builder** window, click **Port 1**.

Orthogonal Polarization 1

In the **Physics** toolbar, click **Attributes** and choose **Orthogonal Polarization**.

Port 2

In the **Model Builder** window, under **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain (ewfd)** click **Port 2**.

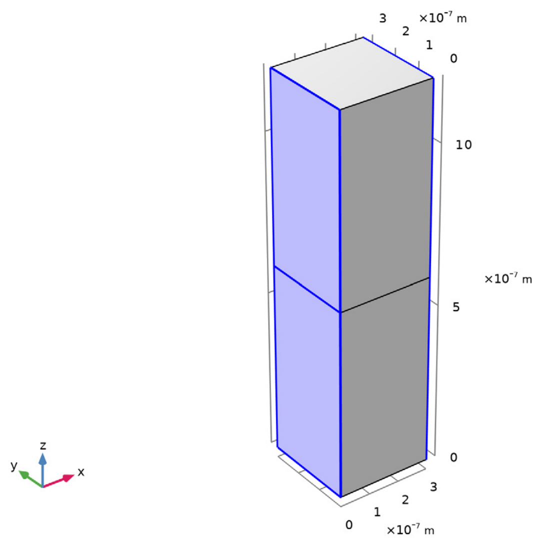
Orthogonal Polarization 1

In the **Physics** toolbar, click **Attributes** and choose **Orthogonal Polarization**.

Periodic Condition 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Periodic Condition**.

2 Select Boundaries 1, 4, 10, and 11 only.



3 In the **Settings** window for **Periodic Condition**, locate the **Boundary Selection** section.

4 Click **Create Selection**.

5 In the **Create Selection** dialog, type `Periodic Condition 1` in the **Selection name** text field.

6 Click **OK**.

7 In the **Settings** window for **Periodic Condition**, locate the **Periodicity Settings** section.

8 From the **Type of periodicity** list, choose **Floquet periodicity**.

9 From the **k-vector for Floquet periodicity** list, choose **From periodic port**.

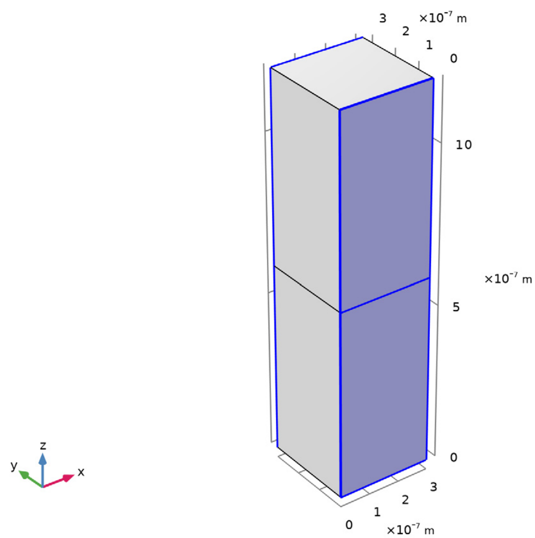
Periodic Condition 2

1 Right-click **Periodic Condition 1** and choose **Duplicate**.

2 In the **Settings** window for **Periodic Condition**, locate the **Boundary Selection** section.

3 Click **Clear Selection**.

4 Select Boundaries 2, 5, 8, and 9 only.



5 Click **Create Selection**.

6 In the **Create Selection** dialog, type `Periodic Condition 2` in the **Selection name** text field.

7 Click **OK**.

STUDY 1

Step 1: Wavelength Domain

1 In the **Model Builder** window, under **Study 1** click **Step 1: Wavelength Domain**.

2 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.

3 In the **Wavelengths** text field, type `lda0`.

4 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)	`range(0[deg],5[deg], 55[deg]) alpha_Brewster range(60[deg],5[deg], 85[deg])`	`deg`

Here, the Brewster angle parameter `alpha_Brewster` was included in the angle sweep.

7 In the **Study** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd)

Next, modify the default plot group **Electric Field (ewfd)** to plot the electric field components, instead of the electric field norm.

1 In the **Settings** window for **3D Plot Group**, click to expand the **Plot Array** section.

2 From the **Array type** list, choose **Linear**.

Multislice 1

1 In the **Model Builder** window, expand the **Electric Field (ewfd)** node, then click **Multislice 1**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd.Ex`.

4 Locate the **Coloring and Style** section. From the **Color table** list, choose **WaveLight**.

5 From the **Scale** list, choose **Linear symmetric**.

Multislice 2

1 Right-click **Results** > **Electric Field (ewfd)** > **Multislice 1** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd.Ey`.

4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Multislice 1**.

Multislice 3

1 Right-click **Multislice 2** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd.Ez`.

Electric Field (ewfd)

1 In the **Model Builder** window, click **Electric Field (ewfd)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Parameter value (alpha (deg))** list, choose **45**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Multislice: Electric field, Cartesian components (V/m)`.

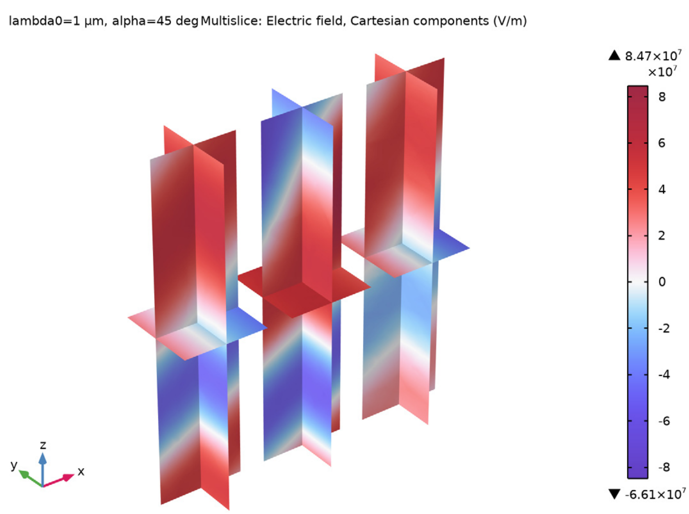
6 In the **Parameter indicator** text field, type `lambda0=1 µm, alpha=45 deg`.

7 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

8 Click the **Show Grid** button in the **Graphics** toolbar.

9 Click the **Zoom Extents** button in the **Graphics** toolbar.

10 In the **Electric Field (ewfd)** toolbar, click **Plot**.



This plot shows that the s (TE) polarization (y component) is out-of-phase with respect to the p (TM) polarization (x and z components).

Reflectance and Transmittance (ewfd)

1 In the **Model Builder** window, under **Results** click **Reflectance, Transmittance, and Absorptance (ewfd)**.

2 In the **Settings** window for **1D Plot Group**, type `Reflectance and Transmittance (ewfd)` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Reflectance and Transmittance (ewfd)** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 Ctrl-click to select table rows 3 and 6–8. That is, select the expressions `ewfd.Rtotal`, `ewfd.Ttotal`, `ewfd.RTtotal`, and `ewfd.Atotal`.

4 Click **Delete**.

Global 2

1 In the **Model Builder** window, right-click **Reflectance and Transmittance (ewfd)** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
R_rhcp		Reflectance, RHCP
R_lhcp		Reflectance, LHCP
T_rhcp		Transmittance, RHCP
T_lhcp		Transmittance, LHCP

4 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

5 Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

6 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Solution** checkbox.

Reflectance and Transmittance (ewfd)

1 In the **Model Builder** window, click **Reflectance and Transmittance (ewfd)**.

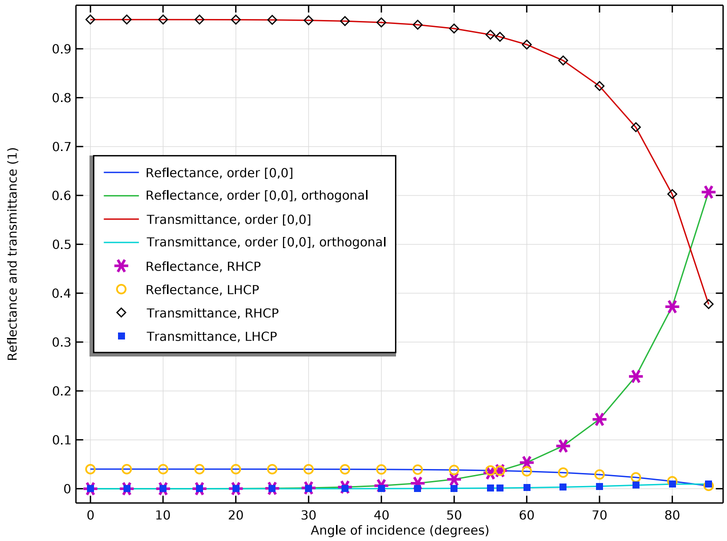
2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 Select the **x-axis label** checkbox. In the associated text field, type `Angle of incidence (degrees)`.

4 In the **y-axis label** text field, type `Reflectance and transmittance (1)`.

5 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

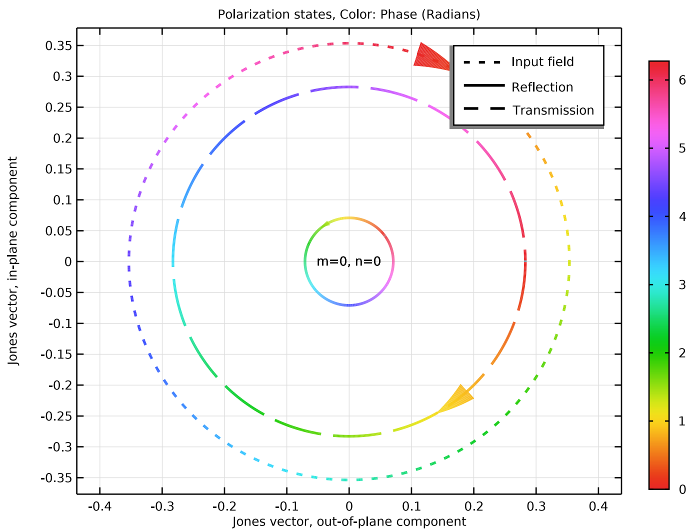
6 In the **Reflectance and Transmittance (ewfd)** toolbar, click **Plot**.



It is clear that the results from the full-field model and the analytical results agree very well.

Polarization Plot (ewfd)

1 In the **Model Builder** window, click **Polarization Plot (ewfd)**.

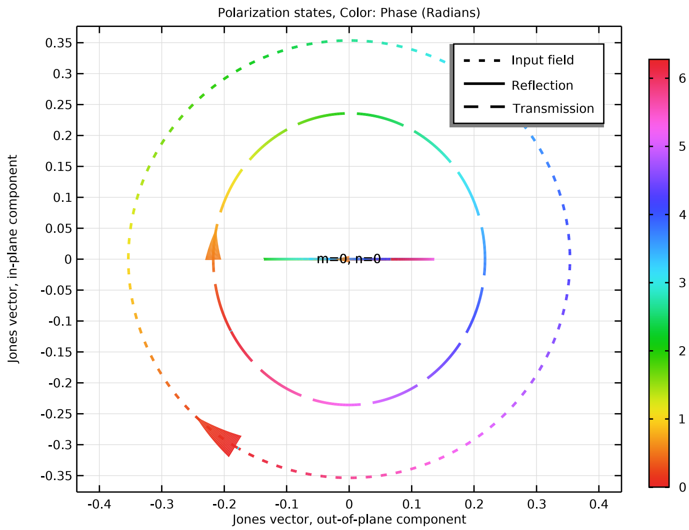


For normal incidence, both the reflected and the transmitted waves have perfectly circular polarization. However, as the arrows point in opposite directions, it is clear that the reflected and transmitted waves have opposite circular polarizations, LHCP and RHCP, respectively. As expected, the input field is RHCP. The size of the circles also indicates that most of the incident intensity is transmitted.

2 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

3 In the **Parameter values (alpha (deg))** list box, select **56.31**, which corresponds to the Brewster angle.

4 In the **Polarization Plot (ewfd)** toolbar, click **Plot**.



At the Brewster angle, the in-plane polarization component for the reflected wave is zero. Thus, the plot shows that the reflected wave has linear polarization in the out-of-plane direction.

COMPONENT 1 (COMP1)

Now, add another physics interface. This time, the circular polarization will be specified by directly picking the appropriate polarization state from the **Port** settings.

ADD PHYSICS

1 In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.

2 Go to the **Add Physics** window.

3 In the tree, select **Optics** > **Wave Optics** > **Electromagnetic Waves, Frequency Domain (ewfd)**.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** checkbox for **Study 1**.

5 Click the **Add to Component 1** button in the window toolbar.

6 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN 2 (EWFD2)

Port 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 In the **Settings** window for **Port**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Port 1**.

4 Locate the **Port Properties** section. From the **Type of port** list, choose **Periodic**.

5 Locate the **Port Mode Settings** section. From the **Polarization** list, choose **Circular polarization**.

   Notice that the default **Circular polarization** for the excited port is **Left-handed**. Since this specifies the polarization of the *outgoing/reflected* waves, the incoming wave will be a right-handed circularly polarized plane wave.

6 In the α_1 text field, type `alpha`.

Port 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 In the **Settings** window for **Port**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Port 2**.

4 Locate the **Port Properties** section. From the **Type of port** list, choose **Periodic**.

5 Locate the **Port Mode Settings** section. From the **Polarization** list, choose **Circular polarization**.

   For the **Port** node on the transmission side, the default **Circular polarization** is **Right-handed**, which is consistent with right-handed circular polarization for the *incoming* wave at the excitation port.

Port 1

In the **Model Builder** window, click **Port 1**.

Orthogonal Polarization 1

In the **Physics** toolbar, click **Attributes** and choose **Orthogonal Polarization**.

Port 2

In the **Model Builder** window, under **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain 2 (ewfd2)** click **Port 2**.

Orthogonal Polarization 1

In the **Physics** toolbar, click **Attributes** and choose **Orthogonal Polarization**.

Periodic Condition 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Periodic Condition**.
2. In the **Settings** window for **Periodic Condition**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Periodic Condition 1**.
4. Locate the **Periodicity Settings** section. From the **Type of periodicity** list, choose **Floquet periodicity**.
5. From the **k-vector for Floquet periodicity** list, choose **From periodic port**.

Periodic Condition 2

1. Right-click **Periodic Condition 1** and choose **Duplicate**.
2. In the **Settings** window for **Periodic Condition**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Periodic Condition 2**.

ADD STUDY

1. In the **Home** toolbar, click **Add Study** to open the **Add Study** window.
2. Go to the **Add Study** window.
3. Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Wavelength Domain**.
4. Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** checkbox for **Electromagnetic Waves, Frequency Domain (ewfd)**.
5. Click the **Add Study** button in the window toolbar.
6. In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Wavelength Domain

1. In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.
2. In the **Wavelengths** text field, type `lda0`.
3. Locate the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.
4. Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)	`range(0[deg],5[deg], 55[deg]) alpha_Brewster range(60[deg],5[deg], 85[deg])`	`deg`

This is easiest done by copying the **Parameter value list** cell contents from the **Study Extensions** settings in **Step 1: Wavelength Domain** under **Study 1** and then pasting the value into this table.

6 In the **Study** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd, ewfd2)

1 In the **Model Builder** window, under **Results** click **Electric Field (ewfd)**.

2 In the **Settings** window for **3D Plot Group**, type `Electric Field (ewfd, ewfd2)` in the **Label** text field.

3 Locate the **Plot Array** section. From the **Array type** list, choose **Square**.

Multislice 4

1 In the **Model Builder** window, under **Results** > **Electric Field (ewfd, ewfd2)** right-click **Multislice 3** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

4 From the **Parameter value (alpha (deg))** list, choose **45**.

5 Locate the **Expression** section. In the **Expression** text field, type `ewfd2.Ex`.

Multislice 5

1 Right-click **Multislice 4** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd2.Ey`.

Multislice 6

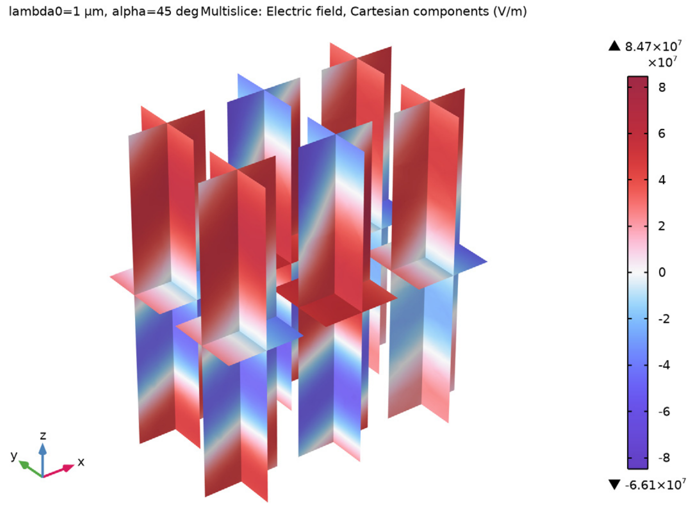
1 Right-click **Multislice 5** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd2.Ez`.

4 Click the **Zoom Extents** button in the **Graphics** toolbar.

5 In the **Electric Field (ewfd, ewfd2)** toolbar, click **Plot**.



Notice that the field distributions are identical for the two different physics interfaces.

Electric Field (ewfd2)

In the **Model Builder** window, under **Results** right-click **Electric Field (ewfd2)** and choose **Delete**.

Reflectance and Transmittance (ewfd2)

In the **Settings** window for **1D Plot Group**, type `Reflectance and Transmittance (ewfd2)` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Reflectance and Transmittance (ewfd2)** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 Ctrl-click to select table rows 3 and 6–8.

4 Click **Delete**.

Global 2

In the **Model Builder** window, under **Results** > **Reflectance and Transmittance (ewfd)** right-click **Global 2** and choose **Copy**.

Global 2

In the **Model Builder** window, right-click **Reflectance and Transmittance (ewfd2)** and choose **Paste Global**.

Reflectance and Transmittance (ewfd2)

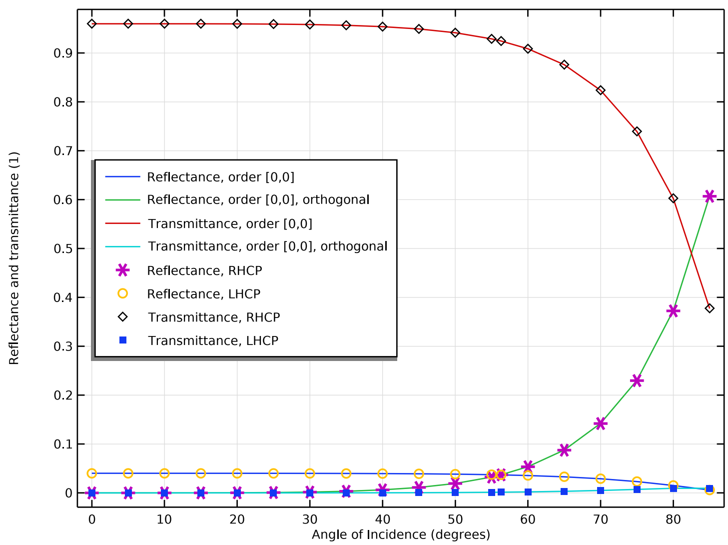
1 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

2 Select the **x-axis label** checkbox. In the associated text field, type `Angle of Incidence (degrees)`.

3 In the **y-axis label** text field, type `Reflectance and transmittance (1)`.

4 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

5 In the **Reflectance and Transmittance (ewfd2)** toolbar, click **Plot**.



Again, the full-wave and the analytical results are in excellent agreement.

COMPONENT 1 (COMP1)

Finally, add a third physics interface. This time, a **Periodic Structure** node will be used. This greatly simplifies the modeling process, as many of the previous modeling steps are now performed automatically.

ADD PHYSICS

1 In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.

2 Go to the **Add Physics** window.

3 In the tree, select **Recently Used** > **Electromagnetic Waves, Frequency Domain (ewfd)**.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** checkboxes for **Study 1** and **Study 2**.

5 Click the **Add to Component 1** button in the window toolbar.

6 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN 3 (EWFD3)

Periodic Structure 1

1 In the **Physics** toolbar, click **Domains** and choose **Periodic Structure**.

2 In the **Settings** window for **Periodic Structure**, locate the **Port Mode Settings** section.

3 From the **Polarization** list, choose **Circular polarization**. As the default **Circular polarization** is **Right-handed**, this will define an incoming right-handed circularly polarized plane wave.

4 In the α_1 text field, type `alpha`.

5 Expand the **Periodic Structure 1** node, to see that the **Periodic Structure** node automatically creates **Periodic Port** and **Floquet Periodic Condition** subnodes.

6 Select the **Periodic Port 1** node. Since the **Polarization** setting on the **Periodic Structure** node represents the polarization state for the incident waves, the excited **Periodic Port** node automatically gets left-handed circular polarization as the setting on the **Periodic Port** node represents the state for the outgoing (reflected) wave. This is also consistent with how the polarization was specified for **Port 1** for the **Electromagnetic Waves, Frequency Domain 2** interface.

7 Select the **Periodic Port 2** node, to see that **Periodic Port** automatically gets the same polarization as **Port 2** in the **Electromagnetic Waves, Frequency Domain 2** interface.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Wavelength Domain**.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** checkboxes for **Electromagnetic Waves, Frequency Domain (ewfd)** and **Electromagnetic Waves, Frequency Domain 2 (ewfd2)**.

5 Click the **Add Study** button in the window toolbar.

6 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 3

Step 1: Wavelength Domain

1 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.

2 In the **Wavelengths** text field, type `lda0`.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)	`range(0[deg],5[deg], 55[deg]) alpha_Brewster range(60[deg],5[deg], 85[deg])`	`deg`

Again, copy the angles for **Parameter value list** from any of the two previous **Wavelength Domain** study steps.

6 In the **Study** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd, ewfd2, ewfd3)

1 In the **Model Builder** window, under **Results** click **Electric Field (ewfd, ewfd2)**.

2 In the **Settings** window for **3D Plot Group**, type `Electric Field (ewfd, ewfd2, ewfd3)` in the **Label** text field.

Multislice 7

1 In the **Model Builder** window, under **Results** > **Electric Field (ewfd, ewfd2, ewfd3)** right-click **Multislice 4** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

4 Locate the **Expression** section. In the **Expression** text field, type `ewfd3.Ex`.

Multislice 8

1 Right-click **Multislice 7** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd3.Ey`.

Multislice 9

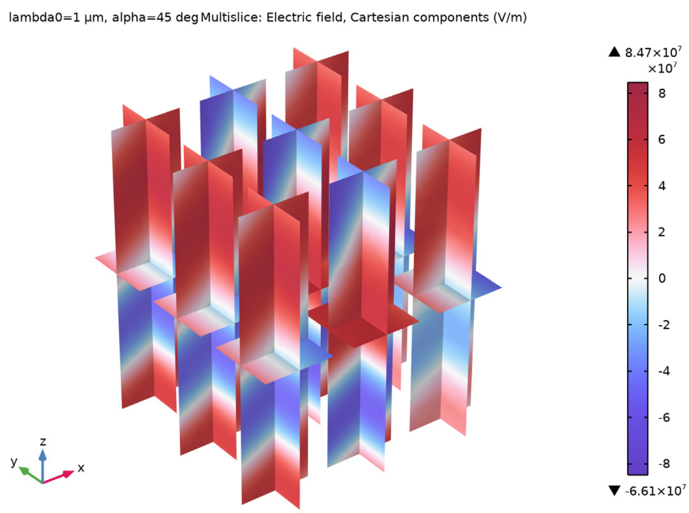
1 Right-click **Multislice 8** and choose **Duplicate**.

2 In the **Settings** window for **Multislice**, locate the **Expression** section.

3 In the **Expression** text field, type `ewfd3.Ez`.

4 In the **Electric Field (ewfd, ewfd2, ewfd3)** toolbar, click **Plot**.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.



It is clear that the field distributions are almost the same for all three different modeling approaches.

Electric Field (ewfd3)

In the **Model Builder** window, under **Results** right-click **Electric Field (ewfd3)** and choose **Delete**.

Reflectance and Transmittance (ewfd3)

In the **Settings** window for **1D Plot Group**, type `Reflectance and Transmittance (ewfd3)` in the **Label** text field.

Global 1

1 In the **Model Builder** window, expand the **Reflectance and Transmittance (ewfd3)** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 Ctrl-click to select table rows 3 and 6–8.

4 Click **Delete**.

Global 2

In the **Model Builder** window, under **Results > Reflectance and Transmittance (ewfd)** right-click **Global 2** and choose **Copy**.

Global 2

In the **Model Builder** window, right-click **Reflectance and Transmittance (ewfd3)** and choose **Paste Global**.

Reflectance and Transmittance (ewfd3)

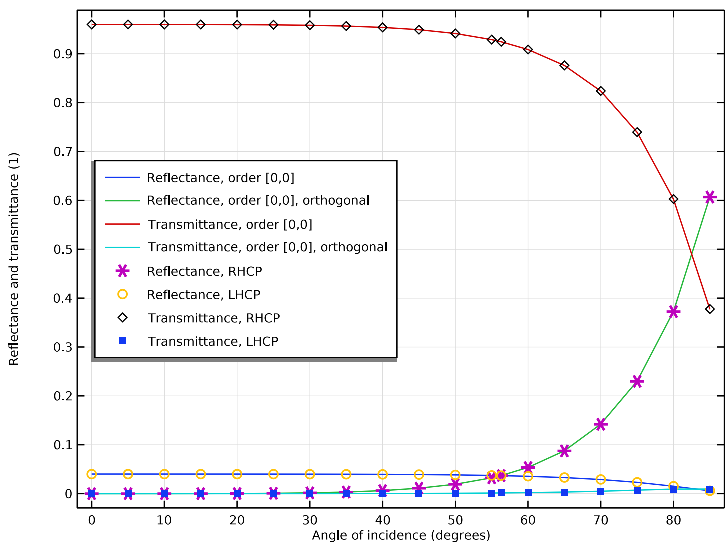
1 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

2 Select the **x-axis label** checkbox. In the associated text field, type `Angle of incidence (degrees)`.

3 In the **y-axis label** text field, type `Reflectance and transmittance (1)`.

4 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

5 In the **Reflectance and Transmittance (ewfd3)** toolbar, click **Plot**.



This plot confirms that all three ways of modeling a circularly polarized plane wave reflected by a dielectric interface produce the same results, in good agreement with the analytical results.

Electric Field Vectors

Finally, create an arrow plot of the electric fields and the port mode fields for the three different physics interfaces, demonstrating that the incident and transmitted waves indeed are right-handed circularly polarized plane waves.

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Electric Field Vectors` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (alpha (deg))** list, choose **45**.

Arrow Volume 1

1 Right-click **Electric Field Vectors** and choose **Arrow Volume**.

2 In the **Settings** window for **Arrow Volume**, locate the **Arrow Positioning** section.

3 Find the **X grid points** subsection. In the **Points** text field, type `1`.

4 Find the **Y grid points** subsection. In the **Points** text field, type `1`.

5 Find the **Z grid points** subsection. In the **Points** text field, type `2`.

Arrow Volume 2

1 Right-click **Arrow Volume 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Volume**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Energy and power** > **ewfd.Poavx,..., ewfd.Poavz - Power flow, time average**.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

Arrow Volume 3

1 In the **Model Builder** window, under **Results** > **Electric Field Vectors** right-click **Arrow Volume 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Volume**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

4 From the **Parameter value (alpha (deg))** list, choose **45**.

5 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain 2** > **Electric** > **ewfd2.Ex,ewfd2.Ey,ewfd2.Ez - Electric field**.

6 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

Arrow Volume 4

1 Right-click **Arrow Volume 3** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Volume**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

4 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain 3** > **Electric** > **ewfd3.Ex,ewfd3.Ey,ewfd3.Ez - Electric field**.

5 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

Arrow Surface 1

1 In the **Model Builder** window, right-click **Electric Field Vectors** and choose **Arrow Surface**.

2 In the **Settings** window for **Arrow Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Ports** > **Electric mode field amplitudes** > **ewfd.Eamplx_1,...,ewfd.Eamplz_1 - Electric mode field amplitude, port 1**.

3 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type 1.

Selection 1

1 Right-click **Arrow Surface 1** and choose **Selection**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Port 1**.

Arrow Surface 1

1 In the **Model Builder** window, click **Arrow Surface 1**.

2 In the **Settings** window for **Arrow Surface**, locate the **Coloring and Style** section.

3 Set the slider value to **7.41E-8**.

Arrow Surface 2

1 Right-click **Results** > **Electric Field Vectors** > **Arrow Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Ports** > **Wave vectors** > **ewfd.kModex_1,..., ewfd.kModez_1 - Port mode wave vector, port 1**.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

4 Set the slider value to **1.1E-14**.

Arrow Surface 3

1 Right-click **Arrow Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

4 From the **Parameter value (alpha (deg))** list, choose **45**.

5 Locate the **Expression** section. In the **X-component** text field, type `ewfd2.Eamplx_1`.

6 In the **Y-component** text field, type `ewfd2.Eamply_1`.

7 In the **Z-component** text field, type `ewfd2.Eamplz_1`.

8 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

Arrow Surface 4

1 Right-click **Arrow Surface 3** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

4 Locate the **Expression** section. In the **X-component** text field, type `ewfd3.Eamplx_1`.

5 In the **Y-component** text field, type `ewfd3.Eamply_1`.

6 In the **Z-component** text field, type `ewfd3.Eamplz_1`.

7 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

Arrow Surface 5

1 In the **Model Builder** window, under **Results** > **Electric Field Vectors** right-click **Arrow Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, locate the **Expression** section.

3 In the **X-component** text field, type `ewfd.Eamplx_2`.

4 In the **Y-component** text field, type `ewfd.Eamply_2`.

5 In the **Z-component** text field, type `ewfd.Eamplz_2`.

Selection 1

1 In the **Model Builder** window, expand the **Arrow Surface 5** node, then click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Port 2**.

Arrow Surface 6

1 In the **Model Builder** window, under **Results** > **Electric Field Vectors** right-click **Arrow Surface 2** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, locate the **Expression** section.

3 In the **X-component** text field, type `ewfd.kModex_2`.

4 In the **Y-component** text field, type `ewfd.kModey_2`.

5 In the **Z-component** text field, type `ewfd.kModez_2`.

Selection 1

1 In the **Model Builder** window, expand the **Arrow Surface 6** node, then click **Selection 1**.

2 In the **Settings** window for **Selection**, locate the **Selection** section.

3 From the **Selection** list, choose **Port 2**.

Arrow Surface 7

1 In the **Model Builder** window, under **Results > Electric Field Vectors** right-click **Arrow Surface 5** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

4 From the **Parameter value (alpha (deg))** list, choose **45**.

5 Locate the **Expression** section. In the **X-component** text field, type `ewfd2.Eamplx_2`.

6 In the **Y-component** text field, type `ewfd2.Eamply_2`.

7 In the **Z-component** text field, type `ewfd2.Eamplz_2`.

8 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

Arrow Surface 8

1 Right-click **Arrow Surface 7** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

4 Locate the **Expression** section. In the **X-component** text field, type `ewfd3.Eamplx_2`.

5 In the **Y-component** text field, type `ewfd3.Eamply_2`.

6 In the **Z-component** text field, type `ewfd3.Eamplz_2`.

7 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

Electric Field Vectors

1 In the **Model Builder** window, click **Electric Field Vectors**.

2 In the **Settings** window for **3D Plot Group**, locate the **Title** section.

3 From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Electric field and electric mode field`.

5 In the **Electric Field Vectors** toolbar, click **Plot**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.

Animation 1

1 In the **Electric Field Vectors** toolbar, click **Animation** and choose **Player**.

2 In the **Settings** window for **Animation**, locate the **Animation Editing** section.

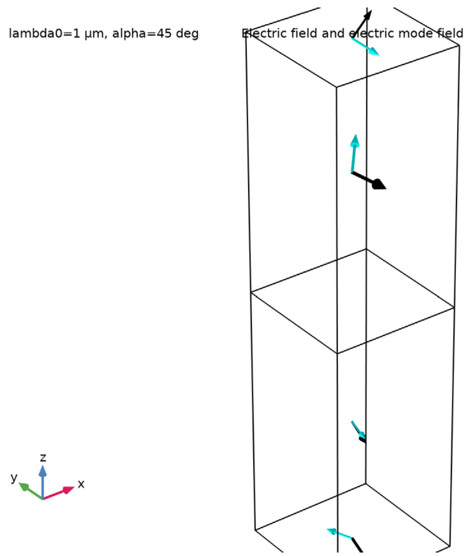
3 From the **Sequence type** list, choose **Dynamic data extension**.

4 Locate the **Frames** section. In the **Number of frames** text field, type 25.

5 Locate the **Playing** section. From the **Repeat** list, choose **Number of iterations**.

6 In the **Number of iterations** text field, type 5.

7 Click the **Play** button in the **Graphics** toolbar.



This animation of the arrow plots shows that the solutions based on the three different physics interfaces are the same. Furthermore, it is clear that the domain fields and the port mode field on the transmission side represent right-handed circularly polarized waves, whereas the mode field for the *outgoing* wave on the excitation port boundary represents a left-handed circularly polarized wave.

Arrow Surface 1

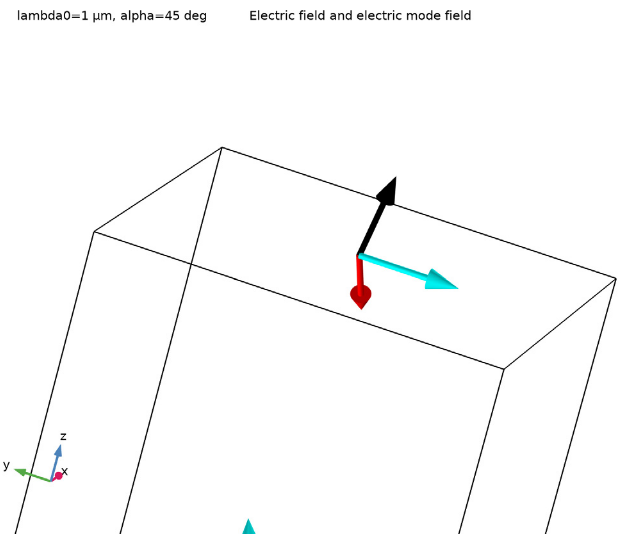
Finally, add the electric mode field amplitude for the **Orthogonal Polarization** node at the excitation port boundary, to verify that the **Port** and the **Orthogonal Polarization** nodes indeed have orthogonal polarizations.

Arrow Surface 9

1 In the **Model Builder** window, under **Results** > **Electric Field Vectors** right-click **Arrow Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Ports** > **Electric mode field amplitudes** > **ewfd.Eamplx_3,...,ewfd.Eamplz_3 - Electric mode field amplitude, port 3**.

Use the **Zoom In** button in the **Graphics** toolbar and the left and right mouse buttons to get a good close up view of the top port boundary with the electric mode field amplitude vectors for the **Port** and the **Orthogonal Polarization** nodes.



Animation 1

1 Click the **Play** button in the **Graphics** toolbar.

This animation shows that the mode field amplitudes for the **Port** (cyan) and the **Orthogonal Polarization** subnode (red) rotates in opposite directions — left-handed circular polarization for the **Port** and right-handed circular polarization for the **Orthogonal Polarization** node.