Created in COMSOL Multiphysics 6.1

Ray Release Based on a Plane Electromagnetic Wave

Introduction

This tutorial shows how to set up a ray release based on the incident electric field at a boundary. First the Electromagnetic Waves, Frequency Domain interface is used to solve for the electric field of a plane wave. Then rays are released with initial intensity and polarization matching that of the electric field at the releasing boundary.

Model Definition

This model offers some guidelines for multiscale modeling of electromagnetic wave propagation. The main idea is to use the Electromagnetic Waves, Frequency Domain interface to compute the electric field over a region that is similar in size to the wavelength, then use the Geometrical Optics interface to model propagation over longer distances.

MOTIVATION

The Electromagnetic Waves, Frequency Domain interface can be used to obtain an accurate full-wave solution to Maxwell's Equations using the finite element method (FEM). However, the finite element mesh must be fine enough to resolve the individual oscillations of the electric field. Following the *Nyquist criterion*, the mesh should have at least 10 linear or 5 second-order mesh elements per wavelength. For example, if the wavelength is 500 nm and the domain is a cube that is 10 µm on each side, then the simulation domain is about 20 wavelengths in each direction. For second-order shape functions, a swept mesh of this domain would include one million elements. This 10 µm cube would be a very difficult problem to solve on a desktop computer; a room several meters in width is simply infeasible.

In contrast, the Geometrical Optics interface can be used to model electromagnetic wave propagation over very large distances because it does not require the mesh to be fine enough to resolve individual wavelengths. However, a ray tracing approach treats each ray as a wavefront that is locally plane, and therefore effects like diffraction are not considered.

One compromise is to solve Maxwell's Equations using the Electromagnetic Waves, Frequency Domain interface in the immediate vicinity of any object similar in size to the wavelength, and then trace rays over longer distances that lack such fine geometric details. As the rays are released, information about their initial intensity, polarization, and phase can be obtained from the electric field in the adjacent domain.

Although the rays in this example are traced over a distance comparable to the waveguide, this is mainly for visualization and validation purposes. The rays could easily propagate over any arbitrarily large number of wavelengths.

RAY INTENSITY INITIALIZATION

In the Geometrical Optics interface, ray intensity can be initialized from an electric field by converting the electric field amplitude to a set of Stokes parameters,

$$\begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I(0,0) + I(90°,0) \\ I(0,0) - I(90°,0) \\ I(45°,0) - I(135°,0) \\ I\left(45°,\frac{\pi}{2}\right) - I\left(135°,\frac{\pi}{2}\right) \end{bmatrix} = \frac{c\varepsilon_0 n}{2}\begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2|E_x||E_y|\cos\delta \\ 2|E_x||E_y|\sin\delta \end{bmatrix}$$

where the ray is assumed to propagate in the z-direction so that the transverse electric field components are E_x and E_y (SI unit: V/m). If the light is not monochromatic, then time-averaging of the electric field components is required. The Stokes parameters themselves have units of intensity (W/m^2). In addition,

- $c = 299{,}792{,}458$ m/s is the speed of light in a vacuum,
- $\varepsilon_0 = 8.854187817 \times 10^{-12}$ F/m is the permittivity of vacuum, and
- n (dimensionless) is the refractive index.

The medium is assumed to be nonmagnetic ($\mu_r = 1$). The middle column shows how the Stokes parameters can be defined phenomenologically. Here $I(\theta,\delta)$ (SI unit: W/m^2) is the intensity that would be transmitted by a polarizer that only accepts light that is polarized at angle θ, with a phase delay of δ between the x- and y- components. With this definition, the second, third, and fourth Stokes parameters each describe the difference in intensity between one polarization state and an orthogonal state.

- s_0 is the total ray intensity,
- s_1 is the preference for horizontal polarization over vertical polarization,
- s_2 is the preference for polarization in the direction $y = x$, over polarization in the direction $y = -x$, and
- s_3 is the preference for right-handed circular polarization over left-handed circular polarization.

Altogether, the four Stokes parameters are capable of characterizing any polarization state of a quasi-monochromatic wave, including linearly polarized, circularly polarized, elliptically polarized, unpolarized, and partially polarized. If the light is monochromatic, or otherwise fully polarized, then

$$s_0^2 = s_1^2 + s_2^2 + s_3^2$$

MODEL SETUP

The electric field of a plane wave is first computed using the Electromagnetic Waves, Frequency Domain interface. Depending on the application, sometimes the Electromagnetic Waves, Beam Envelopes interface can be used instead.

The model geometry is a block that is several wavelengths long. A plane wave propagates in the positive z-direction. To excite the wave, the **Port** boundary condition is used at one face parallel to the xy-plane. The **Port** is used to excite the wave instead of the **Scattering Boundary Condition** because the **Port** allows the input power to be specified more easily.

The **Scattering Boundary Condition** is used at the other end of the domain, to absorb the outgoing wave and prevent any energy from being reflected back toward the **Port**. For best results, the **Scattering Boundary Condition** should be used to absorb waves at normal incidence. If waves are likely to be incident at very large angles to the surface normal, a better approach is to use a **Perfectly Matched Layer**.

On the two sides of the domain where $\mathbf{n} \times \mathbf{E} = \mathbf{0}$, the default **Perfect Electric Conductor** boundary condition is used. On the two other sides, where $\mathbf{n} \cdot \mathbf{E} = \mathbf{0}$, the **Perfect Magnetic Conductor** condition is applied.

After solving for the electric field using the **Wavelength Domain** study (the **Frequency Domain** study is also a valid choice), the Geometrical Optics interface is used to continue tracing rays outside of the domain. The **Release from Electric Field** node is used to release rays directly from the boundary.

In the settings for the **Ray Tracing** study, it is crucial that the correct study is chosen in the **Values of variables not solved for** section (typically a **Frequency Domain** or **Wavelength Domain** study step is chosen), or else the rays might be released with zero intensity.

Results and Discussion

A **Multislice** plot of the x-component of the electric field is shown in Figure 1. Then the x-component of the electric field for both the FEM calculation and the ray tracing solution are shown side-by-side in Figure 2. It is clear that the amplitude, direction, and phase of the electric field along the rays matches that of the FEM solution in the adjacent domain. This can also be shown by plotting the electric field along one of the edges of the domain, then plotting the electric field on rays as a function of average position with a **Global** plot, as in Figure 3. The sum of the power of all rays can also be evaluated and compared to the input power in the settings for the **Port** feature. The two results are similar but are not exactly the same due to discretization error in the FEM solution.

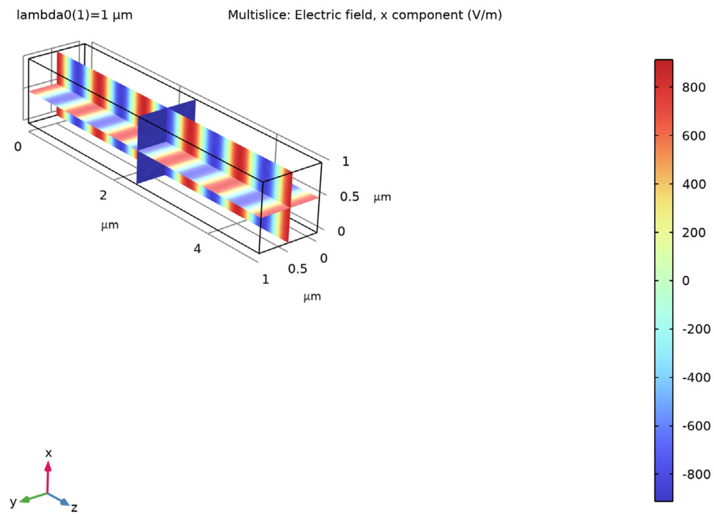

Figure 1: Electric field of a monochromatic plane wave, x-component.

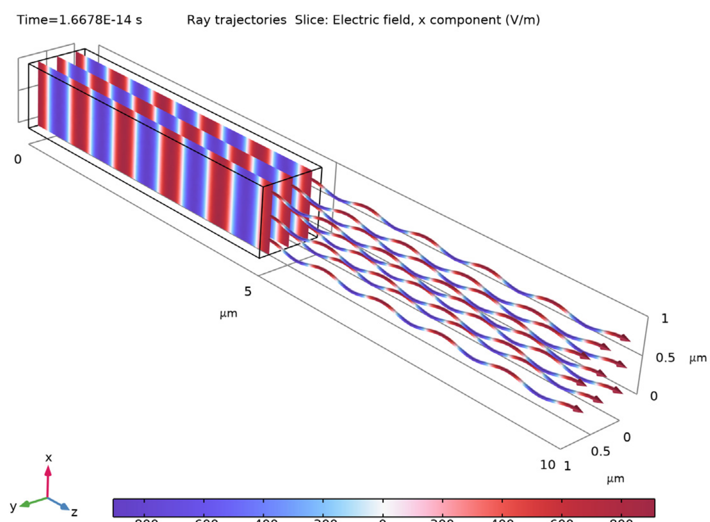

Figure 2: Electric field of a monochromatic plane wave, x-component, computed using FEM within the domain and by releasing rays from its surface.

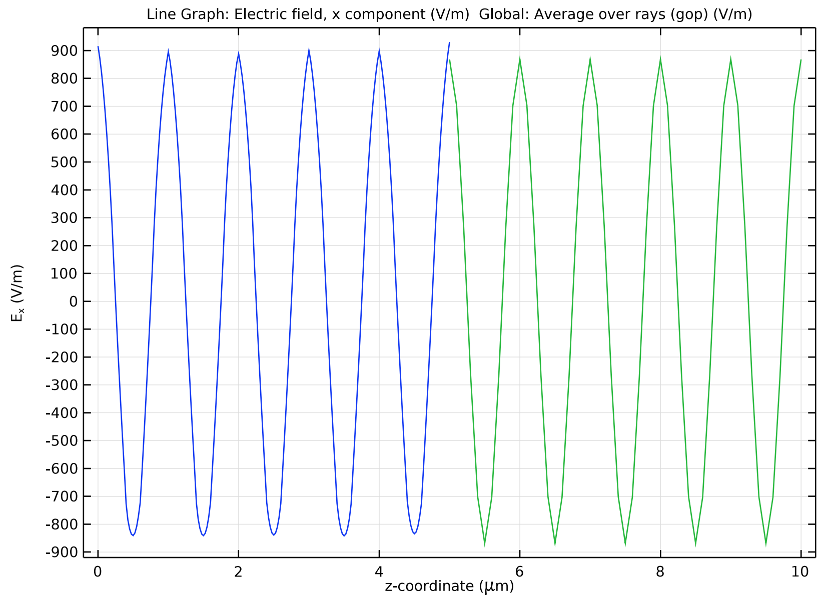

Figure 3: Electric field x-component as a function of the z-coordinate. This illustrates how the released rays are assigned both the amplitude and phase of the incident electric field.

Application Library path: `Ray_Optics_Module/Tutorials/plane_em_wave_to_ray_release`

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 In the table, enter the following settings:

Name	Expression	Value	Description
W	1[um]	1E-6 m	Waveguide width
L	5[um]	5E-6 m	Waveguide length
lam0	1[um]	1E-6 m	Wavelength

GEOMETRY 1

First create the waveguide geometry, which is a simple block.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **µm**.

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 `W`.

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

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

6 Click **Build All Objects**.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Add the boundary conditions. This model uses a **Port** to excite the plane wave, a **Scattering** boundary condition to absorb it, and pairs of **Perfect Electric Conductor** and **Perfect**

Magnetic Conductor conditions on the opposite walls. The **Perfect Electric Conductor** node is already present by default.

Port 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Electromagnetic Waves, Frequency Domain (ewfd)** and choose **Port**.

2 Select Boundary 3 only.

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

4 Specify the $\mathbf{E}_0$ vector as

1	x
0	y
0	z

5 Locate the **Port Properties** section. In the P_{in} text field, type `1e-9[W]`.

6 Locate the **Port Mode Settings** section. In the β text field, type `ewfd.k0`.

Scattering Boundary Condition 1

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

2 Select Boundary 4 only.

Perfect Magnetic Conductor 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Perfect Magnetic Conductor**.

2 Select Boundaries 2 and 5 only.

ADD MATERIAL

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

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

3 In the tree, select **Built-in>Perfect vacuum**.

4 Click **Add to Component** in the window toolbar.

5 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

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 `lam0`.

4 In the **Home** toolbar, click **Compute**.

RESULTS

The default plot shows the electric field norm. This appears quite noisy because the electric field norm should ideally be uniform in this domain. Instead, plot the real part of the electric field amplitude.

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**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Electric>Electric field - V/m>ewfd.Ex - Electric field, x component**.

3 In the **Electric Field (ewfd)** toolbar, click **Plot**. Compare the resulting plot to Figure 1.

ADD PHYSICS

Now set up the Geometrical Optics physics interface.

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>Ray Optics>Geometrical Optics (gop)**.

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

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

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

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 **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Electromagnetic Waves, Frequency Domain (ewfd)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

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

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

GEOMETRICAL OPTICS (GOP)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometrical Optics (gop)**.

2 In the **Settings** window for **Geometrical Optics**, locate the **Ray Release and Propagation** section.

3 In the **Maximum number of secondary rays** text field, type `0`.

4 Locate the **Intensity Computation** section. From the **Intensity computation** list, choose **Compute intensity and power**.

5 Select the **Compute phase** check box.

Release from Electric Field 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Release from Electric Field**.

2 Select Boundary 4 only.

3 In the **Settings** window for **Release from Electric Field**, locate the **Initial Position** section.

4 In the N text field, type `9`.

5 Locate the **Incident Electric Field** section. From the $\mathbf{E}$ list, choose **Electric field (ewfd/wee1)**.

6 Select the **Use frequency from the coupled physics interface as the ray frequency** check box. With this check box selected, the wavelength input in the **Ray Properties** node will be ignored. Instead, the vacuum wavelength will be taken directly from the previous study.

STUDY 2

Step 1: Ray Tracing

1 In the **Model Builder** window, under **Study 2** click **Step 1: Ray Tracing**.

2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

3 From the **Time-step specification** list, choose **Specify maximum path length**.

4 From the **Length unit** list, choose **µm**.

5 In the **Lengths** text field, type `range(0,0.1,5)`.

6 Click to expand the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

7 From the **Method** list, choose **Solution**.

8 From the **Study** list, choose **Study 1, Wavelength Domain**.

9 In the **Home** toolbar, click **Compute**.

RESULTS

The default plot shows the rays being released from the boundary. Modify this default plot and then add a **Slice** plot of the electric field.

Ray Trajectories (gop)

1 In the **Settings** window for **3D Plot Group**, locate the **Color Legend** section.

2 From the **Position** list, choose **Bottom**.

Ray Trajectories 1

1 In the **Model Builder** window, expand the **Ray Trajectories (gop)** node, then click **Ray Trajectories 1**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Coloring and Style** section.

3 Find the **Line style** subsection. From the **Type** list, choose **Tube**.

4 Find the **Point style** subsection. From the **Type** list, choose **Arrow**.

5 From the **Arrow type** list, choose **Arrowhead**.

Deformation 1

1 Right-click **Ray Trajectories 1** and choose **Deformation**.

2 In the **Settings** window for **Deformation**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Geometrical Optics>Intensity and polarization>gop.Ex,gop.Ey,gop.Ez - Electric field**.

3 Locate the **Scale** section.

4 Select the **Scale factor** check box. In the associated text field, type `5E-5`.

Color Expression 1

1 In the **Model Builder** window, click **Color Expression 1**.

2 In the **Settings** window for **Color Expression**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Geometrical Optics>Intensity and polarization>Electric field - V/m>gop.Ex - Electric field, x component**.

3 Locate the **Coloring and Style** section. Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Wave>WaveLight** in the tree.

5 Click **OK**.

Slice 1

1 In the **Model Builder** window, right-click **Ray Trajectories (gop)** and choose **Slice**.

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

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 Click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Electric>Electric field - V/m>ewfd.Ex - Electric field, x component**.

5 Locate the **Plane Data** section. From the **Plane** list, choose **ZX-planes**.

6 In the **Planes** text field, type `3`.

7 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Ray Trajectories 1**.

8 In the **Ray Trajectories (gop)** toolbar, click **Plot**. Compare the resulting plot to Figure 2.

Now add a **1D Plot Group** of the *x*-component of the electric field.

1D Plot Group 3

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 Select the **x-axis label** check box. In the associated text field, type `z-coordinate (\mu m)`.

4 Select the **y-axis label** check box. In the associated text field, type E_x (V/m).

Line Graph 1

1 Right-click **1D Plot Group 3** and choose **Line Graph**.

2 Select Edge 6 only.

3 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Electric>Electric field - V/m>ewfd.Ex - Electric field, x component**.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `z`.

Global 1

1 In the **Model Builder** window, right-click **1D Plot Group 3** and choose **Global**.

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

3 From the **Dataset** list, choose **Ray 1**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
gop.ave(gop.Ex)	V/m	Average over rays (gop)

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `gop.gopaveop1(qz)`.

7 Click to expand the **Legends** section. Clear the **Show legends** check box.

8 In the **1D Plot Group 3** toolbar, click **Plot**. Compare the resulting plot to Figure 3.

Now use a **Global Evaluation** to verify that the sum of the power over all rays matches the specified input power.

Global Evaluation 2

1 In the **Results** toolbar, click **Global Evaluation**.

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

3 From the **Dataset** list, choose **Ray 1**.

4 From the **Time selection** list, choose **Last**.

5 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
gop.sum(gop.Q)	W	Sum over rays (gop)

6 Click **Evaluate**.

The total ray power should be approximately equal to `1e-9 W`, the input power specified in the **Port** node.