



Model created in COMSOL Multiphysics 6.4

# Fresnel Lens

## Introduction

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Fresnel lenses are a special type of optic device that can be extremely thin — as thin as the order of the wavelength of light — and are designed to have focusing, defocusing, and even aberration correction capabilities. A Fresnel lens is designed from an original lens by zoning and folding, as depicted in Figure 1. First, the original lens is sectioned along its height in layers of thickness  $m\lambda/(n-1)$ , where  $m$ ,  $\lambda$ , and  $n$  are the integer Fresnel lens order, the wavelength, and the refractive index, respectively. This corresponds to a  $2m\pi$  radian phase of the light in the lens material. Then the residual parts on the top are folded to the bottom. The concept of this design method is based on the assumption that the incident light is a plane wave with a flat phase front and the material parts of height  $m\lambda/(n-1)$  that are removed do nothing to the phase of the light. Under this assumption, the Fresnel lens is expected to exhibit approximately the same behavior as the original unfolded lens. When a continuous Fresnel lens is designed, it is typically digitized to a digital Fresnel lens for manufacturing reasons.

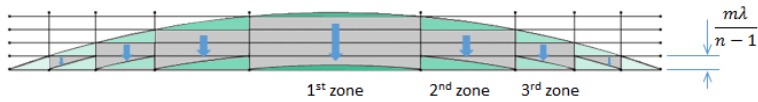


Figure 1: Design of a Fresnel lens.

## Model Definition

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In this model, a plano-convex spherical lens of  $50 \mu\text{m}$  diameter and  $150 \mu\text{m}$  focal length for a  $0.5 \mu\text{m}$  wavelength is converted to a 16-level digitized Fresnel lens of the first order. A plane wave is incident on the bottom boundary, passes through the Fresnel lens, and exits at the exit boundary above the Fresnel lens. The transmitted wave is then propagated to the focal plane.

A comparison is made between the analytical solution using the Fresnel approximation and the solution obtained using both the Electromagnetic Waves, Frequency Domain and the Electromagnetic Waves, Beam Envelopes interfaces. For this model, you get a large speed advantage using the Electromagnetic Waves, Beam Envelopes interface compared to the Electromagnetic Waves, Frequency Domain interface.

In addition to the comparison between the analytical solution and the solutions from the two physics interfaces, the model also demonstrates how to use a spatial fast Fourier transform (FFT) to analyze the scalar field in the focal plane. This postprocessing feature is straightforward to set up compared to manually defining the integral for the Fourier transform and leads to the same result.

Finally, this model explains how to add and run a model method. In this case, the model method helps rebuild the geometry when the geometry parameters have been changed.

### *Results and Discussion*

Figure 2 shows the electric field amplitude around the Fresnel lens and Figure 3 shows the corresponding electric field norm. In the amplitude plot, it is clearly seen that the wavelet exiting from each zone generates a curved wavefront in the air domain and that all wavefronts are in phase and are making one converging wave. In the norm plot, the nonuniformity of the field norm in the lens is a result of Fresnel reflection because the lens surface is not covered by any antireflective coating. You can also see some diffraction at the corner of each digitized step.

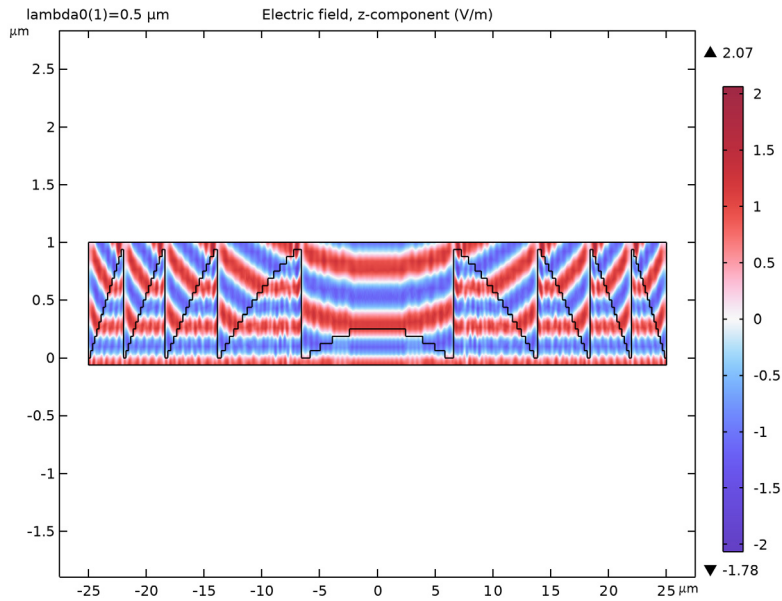


Figure 2: Electric field amplitude around the Fresnel lens. The plot is scaled as  $x:y = 1:10$ .

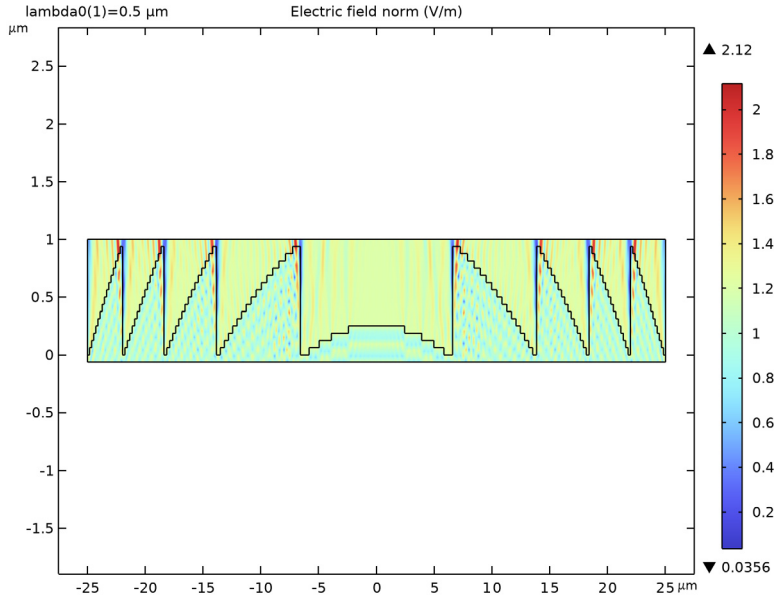


Figure 3: Electric field norm around the Fresnel lens. The plot is scaled as  $x:y = 1:10$ .

Figure 4 shows the phase function of the wave at the exit boundary, just above the Fresnel lens, at  $y = 1 \mu\text{m}$ . This quadratic phase function is approximately the same as in the case of the original unfolded lens.

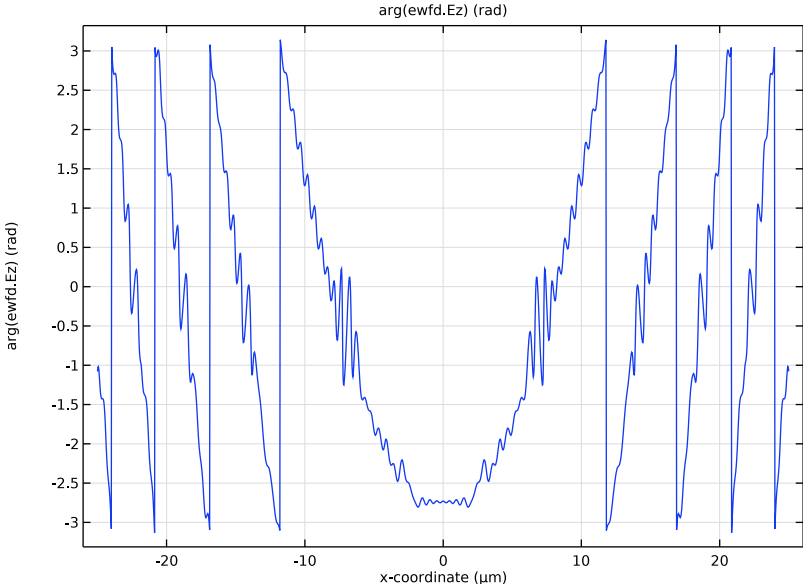


Figure 4: Phase of the electric field at the exit boundary,  $y = 1 \mu\text{m}$ .

Figure 5 is a plot of the electric field norm in the entire air domain, showing that the incident plane wave is focused at the focal plane.

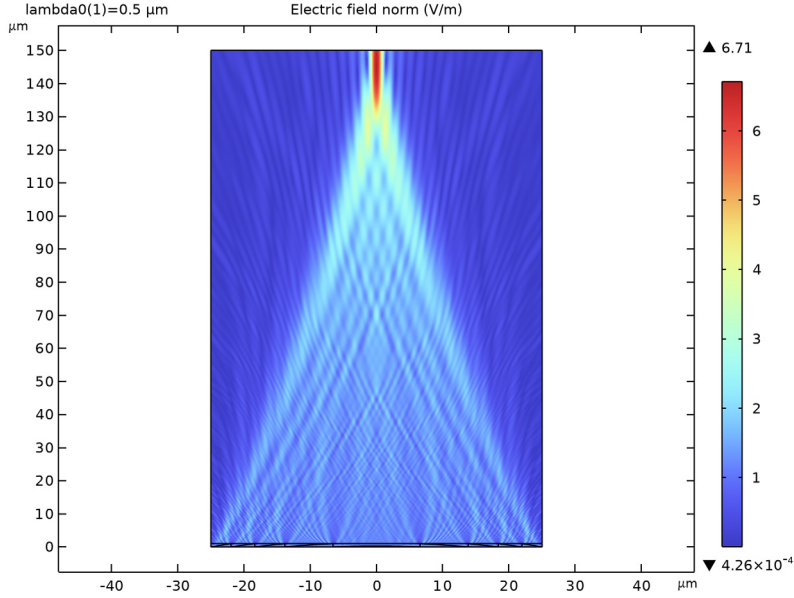


Figure 5: Electric field norm in the air domain. Note that the plot is scaled as  $x:y = 2:1$ .

Finally, Figure 6 is the electric field amplitude at the focal plane. This is a typical image of digitized Fresnel lenses at the focus. There is the main peak at the center, as a result of the first order diffraction, and there is some background caused by the zeroth order and the diffraction orders that were not considered in the design. The magnitude of this background varies depending on the digitization level and the straightness of the surface discontinuities. The result of the full-wave simulation based on the Helmholtz equation is overlaid with the result of the Fresnel approximation, which is computed by the Fresnel diffraction formula

$$E(u, f) = \frac{i}{\sqrt{\lambda f}} \exp(-i(2\pi f/\lambda + \pi u^2/\lambda f)) \int_{-\infty}^{\infty} E(x, 1[\mu m]) \exp(-i\pi x(x - 2u)/(\lambda f)) dx \quad (1)$$

applied to the electric field at the exit boundary at  $y = 1 \mu m$ . Moreover, an additional comparison is made with the result obtained using the built-in spatial fast Fourier

transform feature. The results of the full-wave simulations and the Fresnel approximation are in very good agreement.

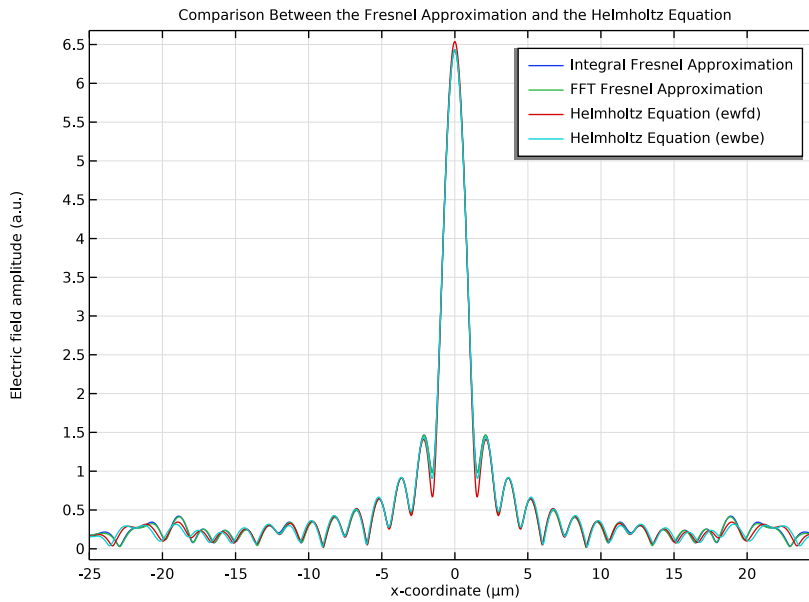


Figure 6: Comparison between the Fresnel approximation (Equation 1, blue curve), the Fresnel integral using the built-in spatial FFT functionality (green curve), and the full-wave simulation, using both the Electromagnetic Waves, Frequency Domain (red curve) and the Electromagnetic Waves, Beam Envelopes (cyan curve) interfaces.

## Reference

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1. Donald. C. O'Shea, Thomas J. Suleski, Alan D. Kathman, and Dennis W. Prather, *Diffractive Optics: Design, Fabrication, and Test*, SPIE Press, 2003.

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**Application Library path:** Wave\_Optics\_Module/Verification\_Examples/  
fresnel\_lens

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## Modeling Instructions




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

## NEW

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


## MODEL WIZARD

- 1 In the **Model Wizard** window, click  **2D**.
- 2 In the **Select Physics** tree, select **Optics > Wave Optics > Electromagnetic Waves, Frequency Domain (ewfd)**.
- 3 Click **Add**.
- 4 In the **Select Physics** tree, select **Optics > Wave Optics > Electromagnetic Waves, Beam Envelopes (ewbe)**.
- 5 Click **Add**.
- 6 Click  **Study**.
- 7 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces > Wavelength Domain**.
- 8 Click  **Done**.

## GLOBAL DEFINITIONS

First add some parameters that will be used for defining the geometry, material, and the study.

### *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 `fresnel_lens_parameters.txt`.

## FRESNEL LENS ZONE

Add a geometry part that defines one zone of the Fresnel lens.

- 1 In the **Model Builder** window, right-click **Global Definitions** and choose **Geometry Parts > 2D Part**.
- 2 In the **Settings** window for **Part**, type `Fresnel Lens Zone` in the **Label** text field.  
Add the input parameter for this part.


3 Locate the **Input Parameters** section. In the table, enter the following settings:

| Name | Default expression | Value | Description |
|------|--------------------|-------|-------------|
| zone | 1                  | 1     | Zone index  |

4 Locate the **Units** section. From the **Length unit** list, choose **μm**, to make all lengths in plots appear in units of μm.

Now, add the internal parameters that will be used when defining the part.


#### *Local Parameters*


- 1 Right-click **Fresnel Lens Zone** and choose **Local Parameters**.
- 2 In the **Settings** window for **Local Parameters**, locate the **Local Parameters** section.
- 3 Click  **Load from File**.
- 4 Browse to the model's Application Libraries folder and double-click the file `fresnel_lens_zone_parameters.txt`.

The parameter  $M_i$  defines the number of discretization levels for the zone. For all zones except the first one, this parameter will be equal to the global parameter  $M$ . However, for the first zone, the parameter  $M_i$  is normally smaller than  $M$ .

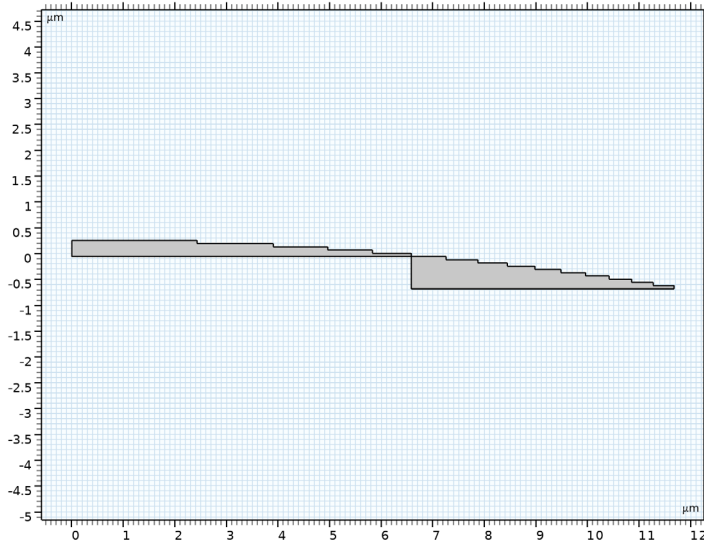
The remaining parameters define the  $x$ - and  $y$ -coordinates for the Fresnel lens zone.

#### *Polygon 1 (pol1)*

- 1 In the **Geometry** toolbar, click  **Polygon**.
- 2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.
- 3 From the **Data source** list, choose **Vectors**.
- 4 In the **x** text field, type `x0 x0 x1 x1 x2 x2 x3 x3 x4 x4 x5 x5 x6 x6 x7 x7 x8 x8 x9 x9 x10 x10 x11 x11 x12 x12 x13 x13 x14 x14 x15 x15 x16 x16`.
- 5 In the **y** text field, type `y0 y1 y1 y2 y2 y3 y3 y4 y4 y5 y5 y6 y6 y7 y7 y8 y8 y9 y9 y10 y10 y11 y11 y12 y12 y13 y13 y14 y14 y15 y15 y16 y16 y0`.
- 6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.
- 7 In the **New Cumulative Selection** dialog, type `Fresnel Lens Zone` in the **Name** text field.
- 8 Click **OK**.

- 9 In the **Geometry** toolbar, click  **Build All**.

Notice that the shape for the first Fresnel lens zone has two parts, where the rightmost part is located below the base line. This part will be removed later when building the Fresnel lens geometry.




## GEOMETRY 1

- 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**, to make all lengths in plots appear in units of μm.

The geometry is created by adding instances of the **Fresnel Lens Zone** part that we just have created. For each zone, the zone index input parameter is changed, to generate the correct coordinates for the zone.

### *Fresnel Lens Zone 1 (pil)*

- 1 In the **Geometry** toolbar, click  **Part Instance** and choose **Fresnel Lens Zone**.
- 2 In the **Settings** window for **Part Instance**, click to expand the **Domain Selections** section.
- 3 Click **New Cumulative Selection**.
- 4 In the **New Cumulative Selection** dialog, type Fresnel Lens in the **Name** text field.
- 5 Click **OK**.
- 6 In the **Settings** window for **Part Instance**, locate the **Domain Selections** section.

7 In the table, enter the following settings:

| Name              | Keep | Physics | Contribute to |
|-------------------|------|---------|---------------|
| Fresnel Lens Zone |      | √       | Fresnel Lens  |

*Fresnel Lens Zone 2 (pi2)*

- 1 Right-click **Fresnel Lens Zone 1 (pi1)** and choose **Duplicate**.
- 2 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.
- 3 In the table, enter the following settings:

| Name | Expression | Value | Description |
|------|------------|-------|-------------|
| zone | 2          | 2     | Zone index  |

*Fresnel Lens Zone 3 (pi3)*

- 1 Right-click **Fresnel Lens Zone 2 (pi2)** and choose **Duplicate**.
- 2 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.
- 3 In the table, enter the following settings:

| Name | Expression | Value | Description |
|------|------------|-------|-------------|
| zone | 3          | 3     | Zone index  |

*Fresnel Lens Zone 4 (pi4)*

- 1 Right-click **Fresnel Lens Zone 3 (pi3)** and choose **Duplicate**.
- 2 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.
- 3 In the table, enter the following settings:

| Name | Expression | Value | Description |
|------|------------|-------|-------------|
| zone | 4          | 4     | Zone index  |


*Fresnel Lens Zone 5 (pi5)*

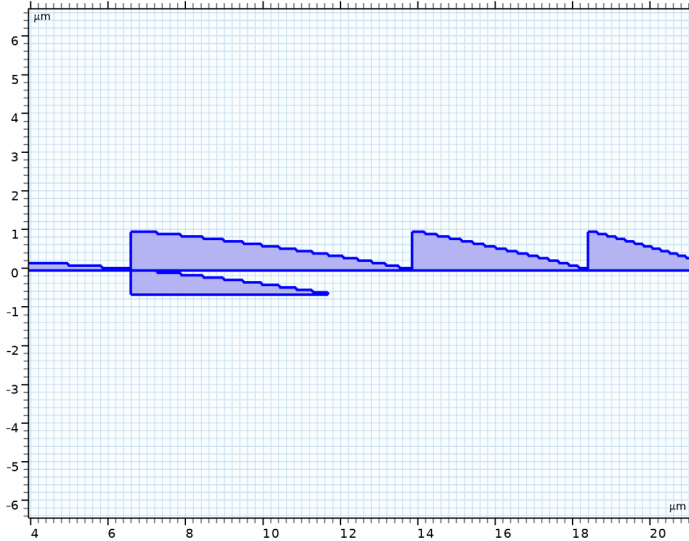
- 1 Right-click **Fresnel Lens Zone 4 (pi4)** and choose **Duplicate**.
- 2 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.
- 3 In the table, enter the following settings:


| Name | Expression | Value | Description |
|------|------------|-------|-------------|
| zone | 5          | 5     | Zone index  |

### *Union 1 (uni1)*



Before proceeding further, make the created half Fresnel lens a single domain, using a Union operation.


- 1 In the **Geometry** toolbar, click  **Booleans and Partitions** and choose **Union**.
- 2 Click in the **Graphics** window and then press Ctrl+A to select all objects.

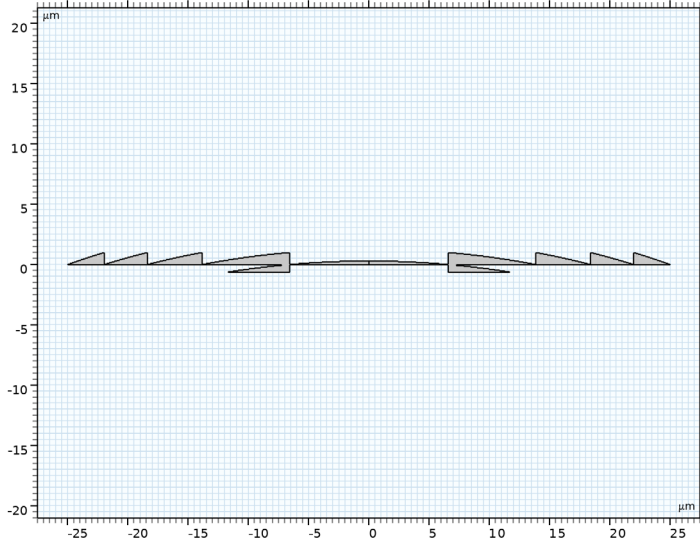


- 3 In the **Model Builder** window, click **Union 1 (uni1)**.
- 4 In the **Settings** window for **Union**, locate the **Union** section.
- 5 Clear the **Keep interior boundaries** checkbox.
- 6 Click  **Build Selected**.

### *Mirror 1 (mir1)*


- 1 In the **Geometry** toolbar, click  **Transforms** and choose **Mirror**.
- 2 Select the object **uni1** only.
- 3 In the **Settings** window for **Mirror**, locate the **Input** section.
- 4 Select the **Keep input objects** checkbox.
- 5 Click  **Build Selected**.

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

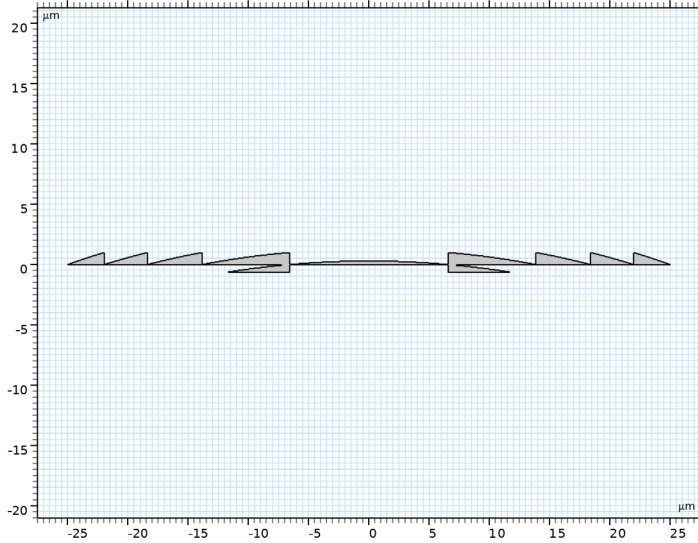


*Union 2 (uni2)*

Make a single domain out of the two lens halves.


- 1 In the **Geometry** toolbar, click  **Booleans and Partitions** and choose **Union**.
- 2 Click in the **Graphics** window and then press Ctrl+A to select both objects.
- 3 In the **Settings** window for **Union**, locate the **Union** section.
- 4 Clear the **Keep interior boundaries** checkbox.

5 Click  **Build Selected**.




#### *Rectangle 1 (r1)*

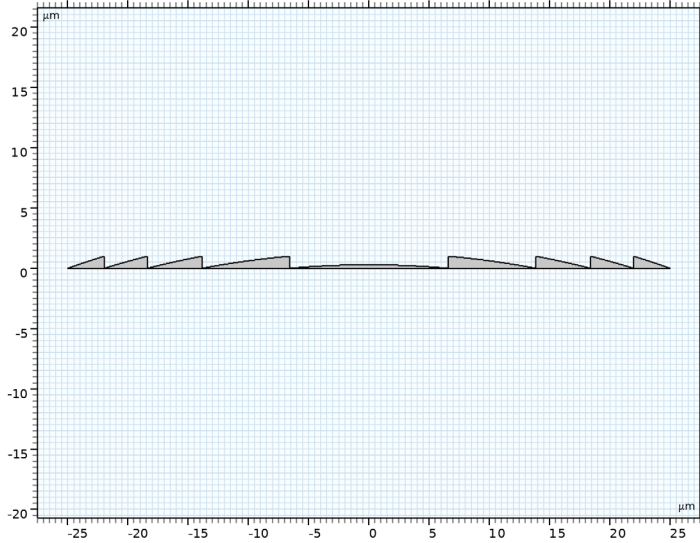
The first zone has a domain that is below the base of the Fresnel lens. That part is removed by making an intersection with a rectangle having the size of the expected bounding box for the Fresnel lens.

- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type  $D$ .
- 4 In the **Height** text field, type  $d+dm$ .
- 5 Locate the **Position** section. In the **x** text field, type  $-D/2$ .
- 6 In the **y** text field, type  $-dm$ .

#### *Intersection 1 (int1)*


- 1 In the **Geometry** toolbar, click  **Booleans and Partitions** and choose **Intersection**.
- 2 Click in the **Graphics** window and then press **Ctrl+A** to select both objects.

3 In the **Settings** window for **Intersection**, click  **Build All Objects**.



### Rectangle 2 (r2)

Now define the propagation domain from the lens to the focal plane.

- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type  $D$ .
- 4 In the **Height** text field, type  $f+dm$ .
- 5 Locate the **Position** section. In the **x** text field, type  $-D/2$ .
- 6 In the **y** text field, type  $-dm$ .
- 7 Click to expand the **Layers** section. In the table, enter the following settings:

| Layer name | Thickness ( $\mu\text{m}$ ) |
|------------|-----------------------------|
| Layer 1    | $d+dm$                      |

### Rectangle 3 (r3)

Now, add two rectangular domains that will be used for perfectly matched layers (PMLs).

- 1 Right-click **Rectangle 2 (r2)** and choose **Duplicate**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type  $1da0$ .

4 Locate the **Position** section. In the **x** text field, type  $-D/2-1da0$ .


*Rectangle 4 (r4)*

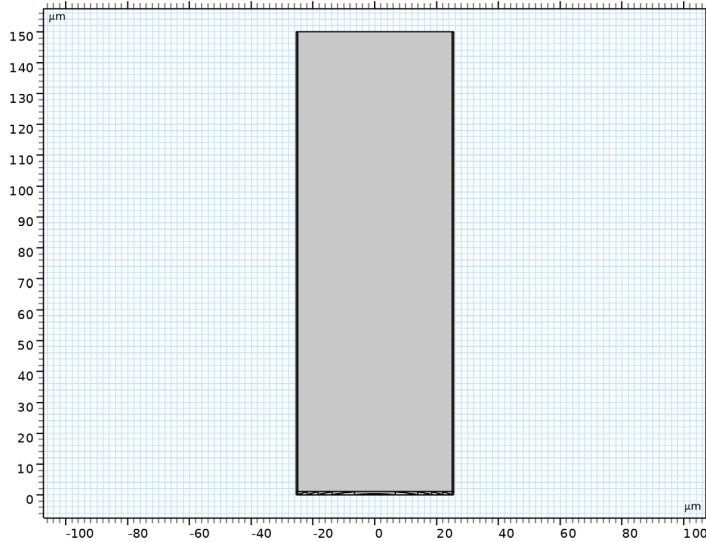
1 Right-click **Rectangle 3 (r3)** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, locate the **Position** section.

3 In the **x** text field, type  $D/2$ .

4 Click  **Build All Objects**.

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



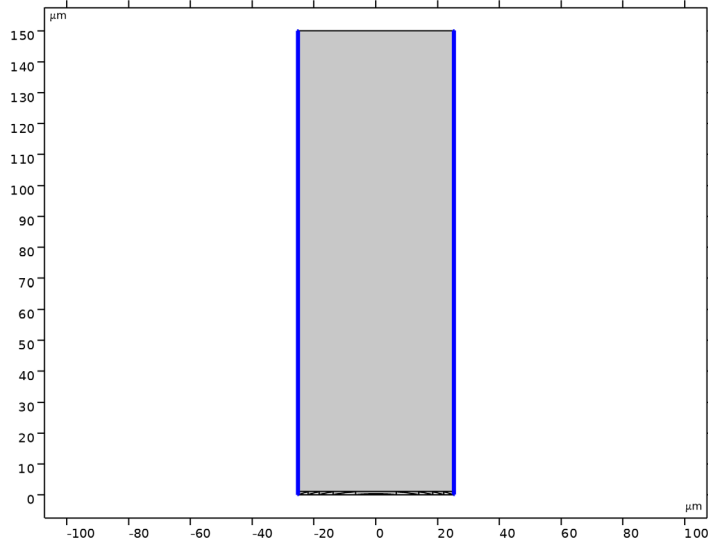
## DEFINITIONS

Add the perfectly matched layer.

*Perfectly Matched Layer 1 (pml1)*

1 In the **Definitions** toolbar, click  **Perfectly Matched Layer**.



2 Select Domains 1, 2, 6, and 7 only.



## MATERIALS

Now add the materials. In COMSOL the first material is applied to all domains, so we start by adding the air to all domains and then add the glass to the Fresnel lens.

### ADD MATERIAL

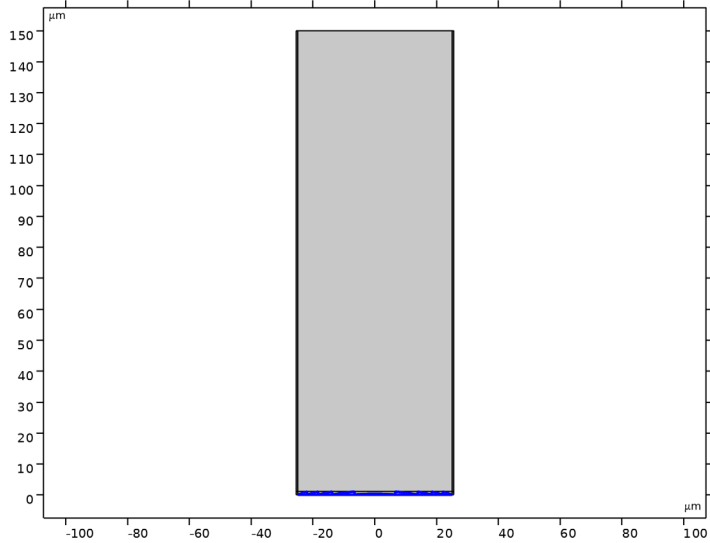
- 1 In the **Materials** toolbar, click  **Add Material** to open the **Add Material** window.
- 2 Go to the **Add Material** window.
- 3 In the tree, select **Built-in > Air**.
- 4 Click the **Add to Component** button in the window toolbar.
- 5 In the **Materials** toolbar, click  **Add Material** to close the **Add Material** window.

## MATERIALS

### Glass

- 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 Glass in the **Label** text field.
- 3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Fresnel Lens**.

4 Click  **Zoom to Selection**.




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

| Property                         | Variable  | Value | Unit | Property group   |
|----------------------------------|---|-------|------|------------------|
| Refractive index, real part      | $n_{iso}$ ; $n_{ii} = n_{iso}$ ,<br>$n_{ij} = 0$    | $n$   | $l$  | Refractive index |
| Refractive index, imaginary part | $k_{iso}$ ; $k_{iii} =$<br>$k_{iso}$ , $k_{ij} = 0$ | 0     | $l$  | Refractive index |


### DEFINITIONS

Now define some selections that will be used later.

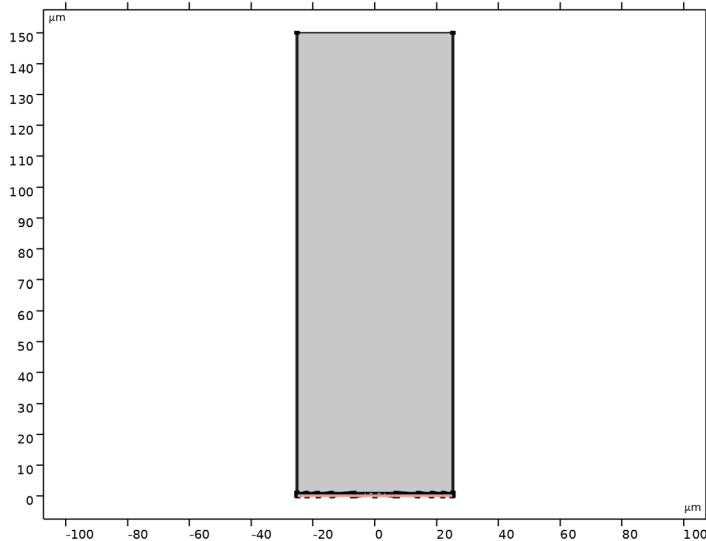
#### Exterior Boundaries

- 1 In the **Definitions** toolbar, click  **Explicit**.
- 2 In the **Settings** window for **Explicit**, type Exterior Boundaries in the **Label** text field.
- 3 Locate the **Input Entities** section. Select the **All domains** checkbox.
- 4 Locate the **Output Entities** section. From the **Output entities** list, choose **Adjacent boundaries**.


#### Input Plane


- 1 In the **Definitions** toolbar, click  **Box**.
- 2 In the **Settings** window for **Box**, type Input Plane in the **Label** text field.

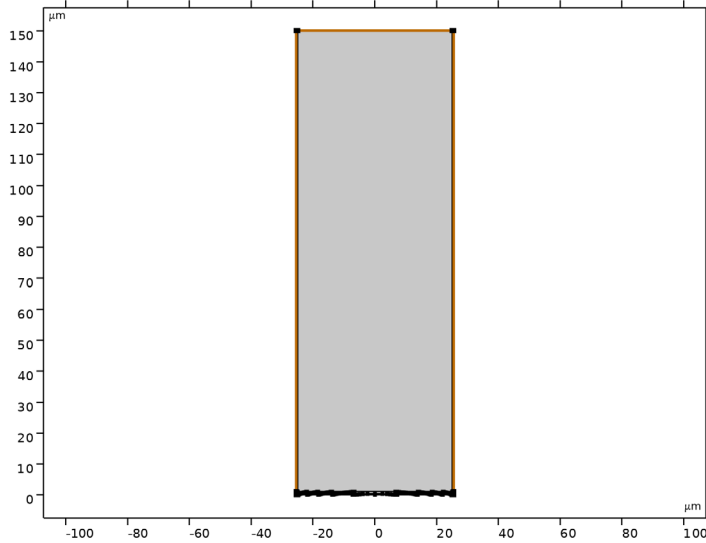
- 3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.
- 4 Locate the **Input Entities** section. From the **Entities** list, choose **From selections**.
- 5 Under **Selections**, click **+ Add**.
- 6 In the **Add** dialog, select **Exterior Boundaries** in the **Selections** list.
- 7 Click **OK**.
- 8 In the **Settings** window for **Box**, locate the **Box Limits** section.
- 9 In the **x minimum** text field, type  $-D/2$ .
- 10 In the **x maximum** text field, type  $D/2$ .
- 11 In the **y minimum** text field, type  $-dm$ .
- 12 In the **y maximum** text field, type  $dm/2$ .
- 13 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.




### Scattering Boundaries

- 1 In the **Definitions** toolbar, click  **Difference**.
- 2 In the **Settings** window for **Difference**, type **Scattering Boundaries** in the **Label** text field.
- 3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.
- 4 Locate the **Input Entities** section. Under **Selections to add**, click **+ Add**.

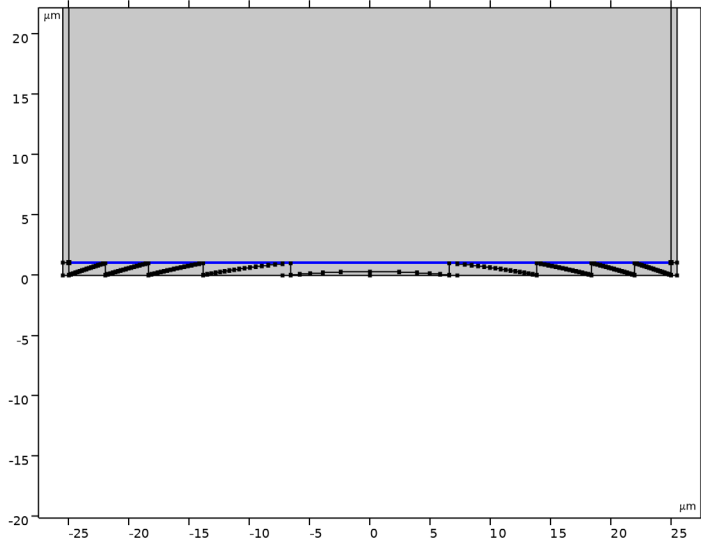
- 5 In the **Add** dialog, select **Exterior Boundaries** in the **Selections to add** list.
- 6 Click **OK**.
- 7 In the **Settings** window for **Difference**, locate the **Input Entities** section.
- 8 Under **Selections to subtract**, click **+ Add**.
- 9 In the **Add** dialog, select **Input Plane** in the **Selections to subtract** list.
- 10 Click **OK**.
- 11 Click the  **Zoom to Selection** button in the **Graphics** toolbar.



#### *Exit Plane*


- 1 In the **Definitions** toolbar, click  **Explicit**.
- 2 In the **Settings** window for **Explicit**, type **Exit Plane** in the **Label** text field.
- 3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.
- 4 Select **Boundary 11** only. This corresponds to the horizontal boundary just above the Fresnel lens.

- 5 Click the  **Zoom to Selection** button in the **Graphics** toolbar.

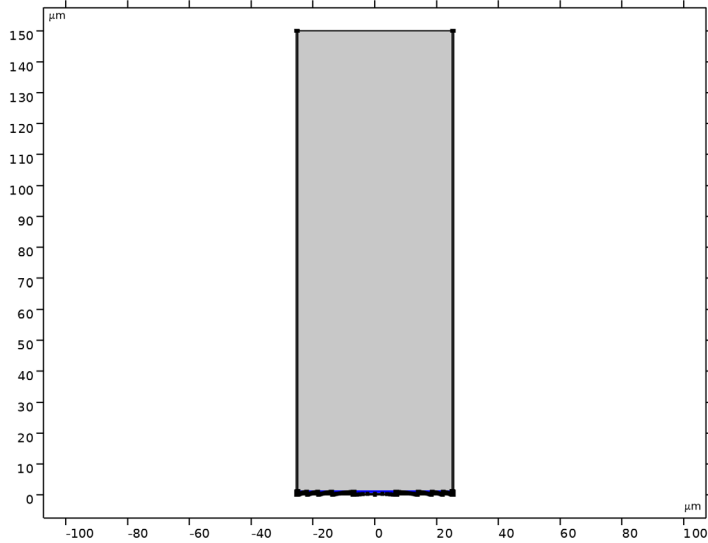


#### *Integration 1 (intop1)*

Before setting up the physics, a nonlocal integration coupling will be defined for the **Exit Plane** selection. This operator will be used for calculating the analytic Fresnel diffraction integral.

- 1 In the **Definitions** toolbar, click  **Nonlocal Couplings** and choose **Integration**.
- 2 In the **Settings** window for **Integration**, locate the **Source Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.


4 From the **Selection** list, choose **Exit Plane**.



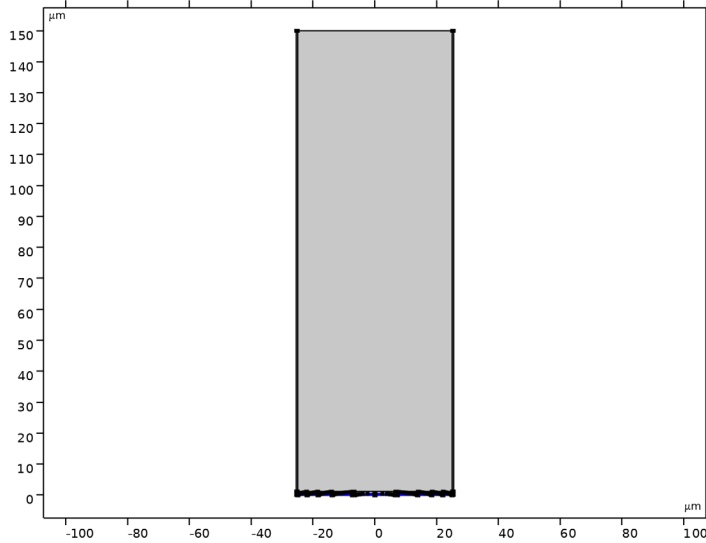
#### **ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFd)**

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (ewfd)**.
- 2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.
- 3 From the **Electric field components solved for** list, choose **Out-of-plane vector**.

#### *Scattering Boundary Condition 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Scattering Boundary Condition**.
- 2 In the **Settings** window for **Scattering Boundary Condition**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Input Plane**.



4 Locate the **Scattering Boundary Condition** section. From the **Incident field** list, choose **Wave given by E field**.

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

|   |   |
|---|---|
| 0 | x |
| 0 | y |
| 1 | z |


6 From the **Order** list, choose **Second order**, to reduce the reflections from radiation incident with a nonnormal direction to this boundary.

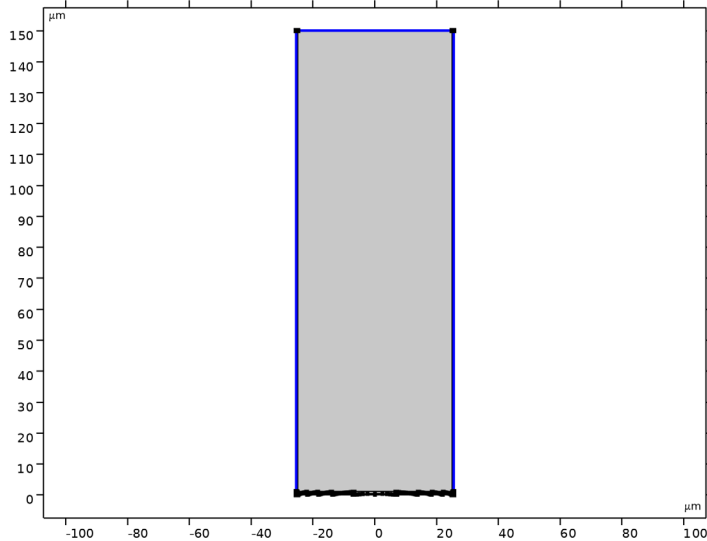
#### *Scattering Boundary Condition 2*

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

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

3 From the **Selection** list, choose **Scattering Boundaries**.

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



- 5 Locate the **Scattering Boundary Condition** section. From the **Order** list, choose **Second order**, to reduce the reflections from radiation incident with a nonnormal direction to this surrounding boundary.

#### **FINE MESH**

Add a name for the mesh, as we later will add a second mesh for the Electromagnetic Waves, Beam Envelopes interface.

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.
- 2 In the **Settings** window for **Mesh**, type Fine Mesh in the **Label** text field.


*Free Triangular 1*

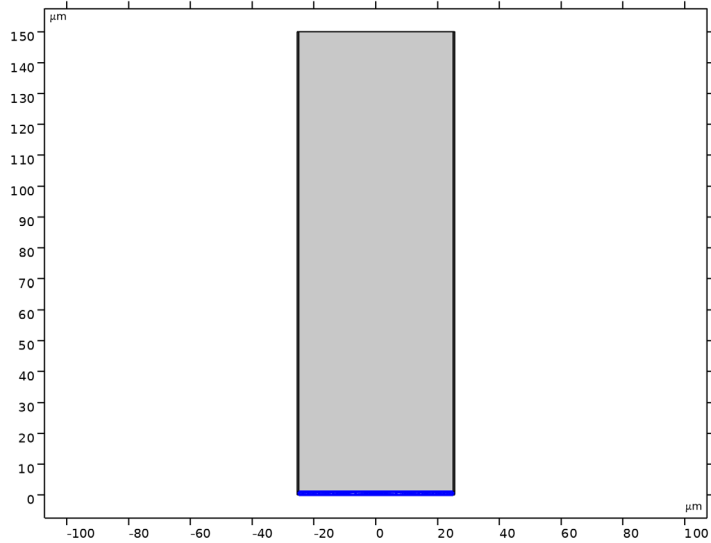
In the **Mesh** toolbar, click  **Free Triangular**.

*Size*

- 1 In the **Model Builder** window, click **Size**.
- 2 In the **Settings** window for **Size**, locate the **Element Size** section.
- 3 Click the **Custom** button.
- 4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type  $1da0/N_{mesh}$ .

### Free Triangular 1

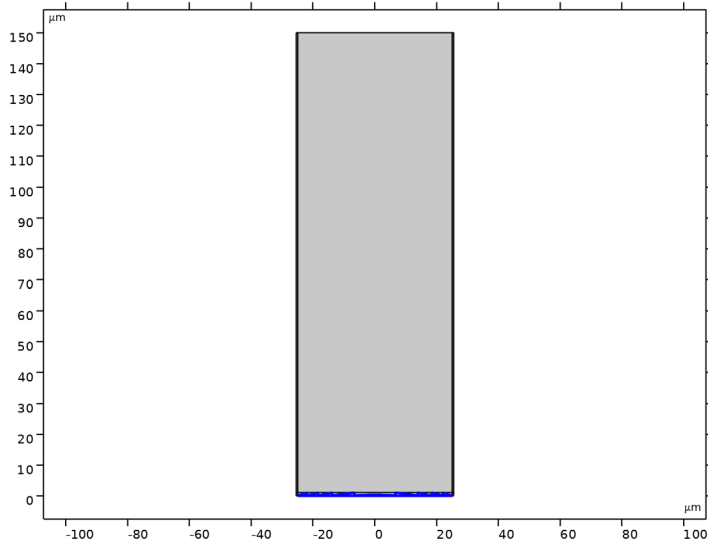
- 1 In the **Model Builder** window, click **Free Triangular 1**.
- 2 In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 Select Domains 3 and 4 only.
- 5 Click  **Zoom to Selection**.



### Size 1


- 1 Right-click **Free Triangular 1** and choose **Size**.

- 2 Select Domain 3 only. The simplest way to do this is to select entity 4 in the **Selection box** and then click the **Remove from Selection** (the minus sign) button in the **Selection toolbar**.



- 3 In the **Settings** window for **Size**, locate the **Element Size** section.
- 4 Click the **Custom** button.
- 5 Locate the **Element Size Parameters** section.
- 6 Select the **Maximum element size** checkbox. In the associated text field, type  $1da0/n/Nmesh$ .

*Mapped 1*

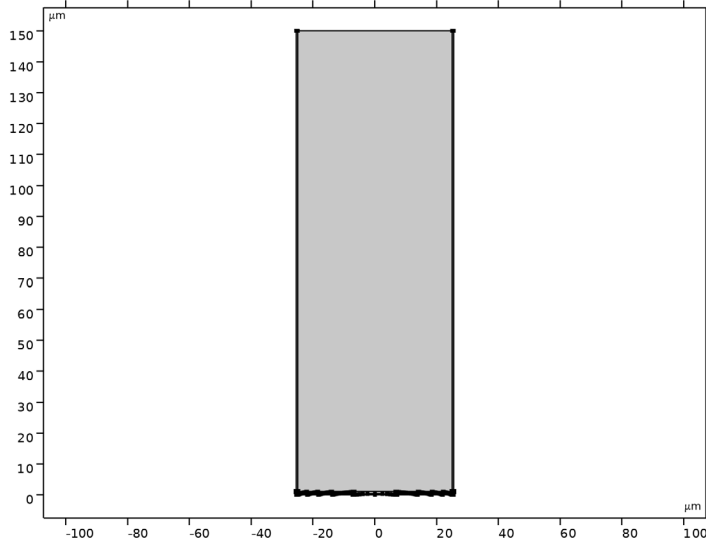
In the **Mesh** toolbar, click  **Mapped**.

*Distribution 1*

A Distribution node defines the number of mesh elements in the PMLs.

- 1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 4 and 301 only.



3 In the **Settings** window for **Distribution**, locate the **Distribution** section.

4 In the **Number of elements** text field, type 8.

## 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 1da0.

4 Locate the **Physics and Variables Selection** section. In the **Solve for** column of the table, under **Component 1 (comp1)**, clear the checkbox for **Electromagnetic Waves, Beam Envelopes (ewbe)**.

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

## RESULTS

### *Electric Field Norm (ewfd)*

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


Change the view now to make the plot wider to improve the aspect ratio.

2 Locate the **Plot Settings** section. From the **View** list, choose **View 1**.

3 Click  **Go to Source**.


## DEFINITIONS

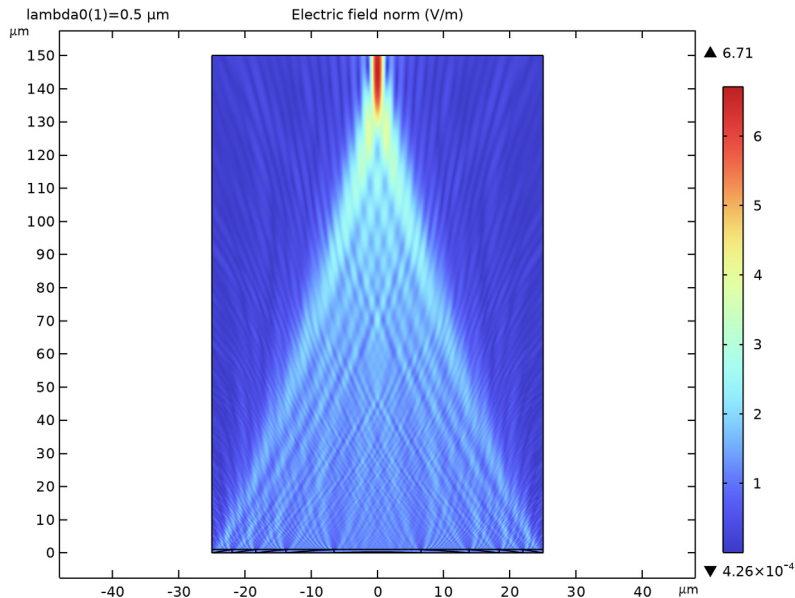
*Axis*

- 1 In the **Model Builder** window, expand the **View 1** node, then click **Axis**.
- 2 In the **Settings** window for **Axis**, locate the **Axis** section.
- 3 From the **View scale** list, choose **Manual**.
- 4 In the **x scale** text field, type 2.
- 5 Click  **Update**.

## RESULTS

*Electric Field Norm (ewfd)*


- 1 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 2 In the **Model Builder** window, under **Results** click **Electric Field Norm (ewfd)**.

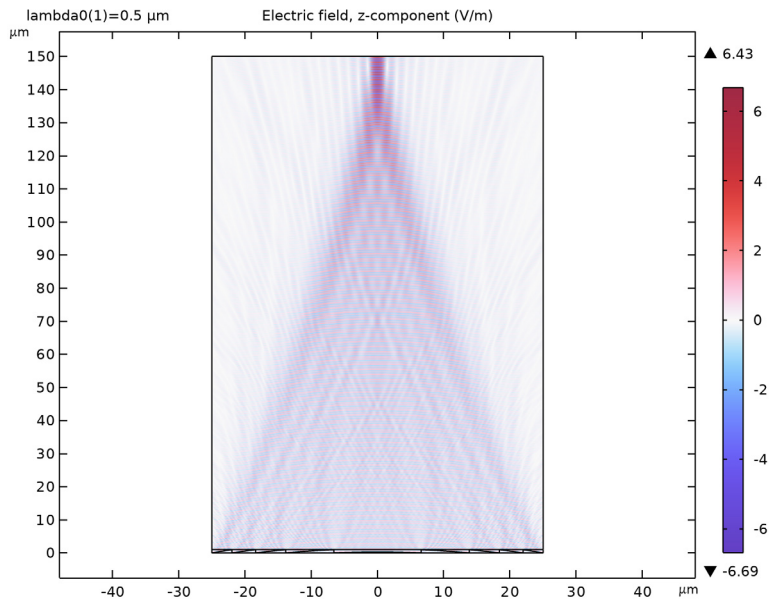


*Electric Field Amplitude (ewfd)*

- 1 Right-click **Electric Field Norm (ewfd)** and choose **Duplicate**.
- 2 In the **Settings** window for **2D Plot Group**, type **Electric Field Amplitude (ewfd)** in the **Label** text field.

### Surface 1

- 1 In the **Model Builder** window, expand the **Electric Field Amplitude (ewfd)** node, then click **Surface 1**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type `ewfd.Ez`.
- 4 Locate the **Coloring and Style** section. From the **Color table** list, choose **WaveLight**.
- 5 From the **Scale** list, choose **Linear symmetric**.
- 6 In the **Electric Field Amplitude (ewfd)** toolbar, click  **Plot**.



### Electric Field Norm Near Lens (ewfd)

- 1 In the **Model Builder** window, right-click **Electric Field Norm (ewfd)** and choose **Duplicate**.
- 2 In the **Settings** window for **2D Plot Group**, type **Electric Field Norm Near Lens (ewfd)** in the **Label** text field.


### DEFINITIONS

Add a new view that will be used to show the near field close to the lens.


### View 3

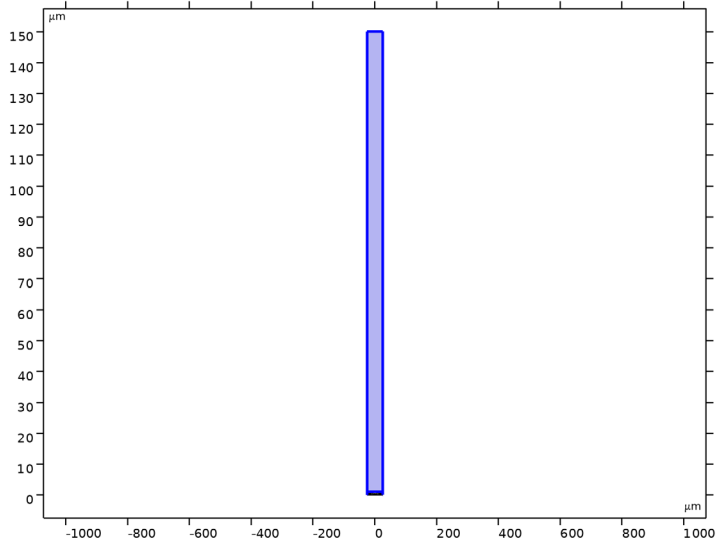
- In the **Model Builder** window, under **Component 1 (comp1)** > **Definitions** right-click **View 1** and choose **Duplicate**.

### Axis

- 1 In the **Model Builder** window, expand the **View 3** node, then click **Axis**.
- 2 In the **Settings** window for **Axis**, locate the **Axis** section.
- 3 In the **x scale** text field, type 1.
- 4 In the **y scale** text field, type 10.
- 5 Click  **Update**.


### Hide for Physics I


- 1 In the **Model Builder** window, right-click **View 3** and choose **Hide for Physics**.
- 2 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 3 Select Domains 1, 2, and 5–7 only.

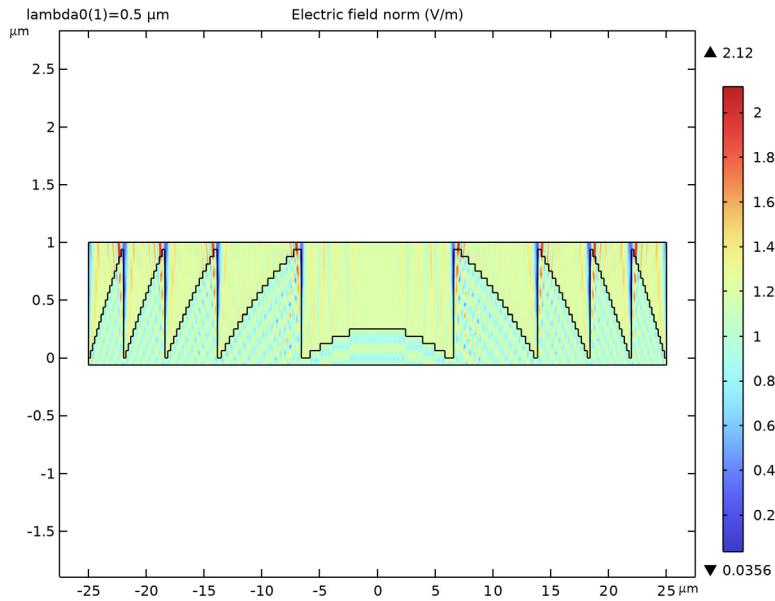


## RESULTS


### Electric Field Norm Near Lens (ewfd)


- 1 In the **Model Builder** window, under **Results** click **Electric Field Norm Near Lens (ewfd)**.
- 2 In the **Settings** window for **2D Plot Group**, locate the **Plot Settings** section.
- 3 From the **View** list, choose **View 3**.
- 4 In the **Electric Field Norm Near Lens (ewfd)** toolbar, click  **Plot**.

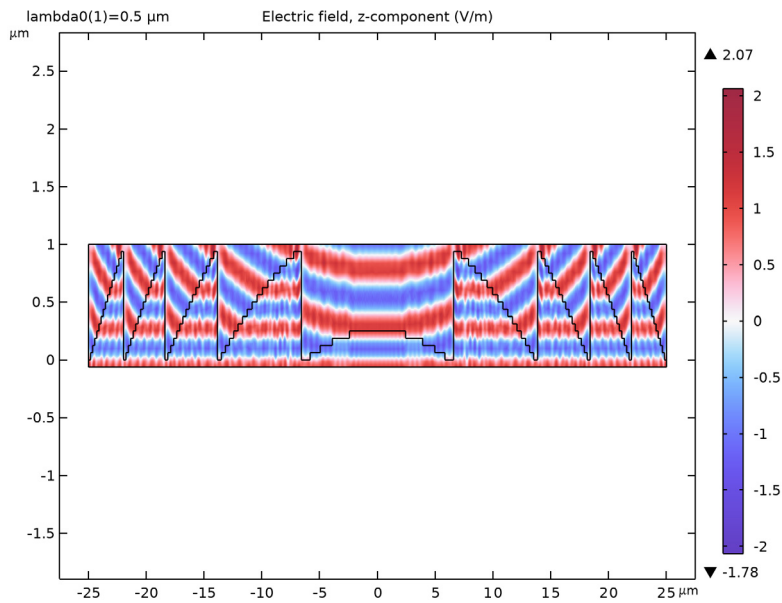
- 5 Click the  **Zoom Extents** button in the **Graphics** toolbar.



*Electric Field Amplitude Near Lens (ewfd)*


- 1 In the **Model Builder** window, right-click **Electric Field Amplitude (ewfd)** and choose **Duplicate**.
- 2 In the **Settings** window for **2D Plot Group**, type **Electric Field Amplitude Near Lens (ewfd)** in the **Label** text field.
- 3 Locate the **Plot Settings** section. From the **View** list, choose **View 3**.
- 4 In the **Electric Field Amplitude Near Lens (ewfd)** toolbar, click  **Plot**.

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



#### *Electric Field Amplitude at Exit Plane (ewfd)*

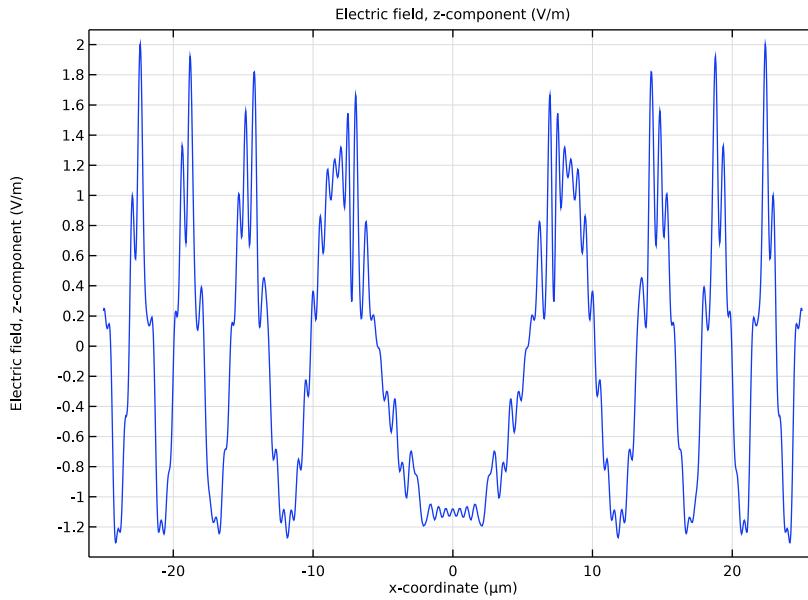
Now create two line plots displaying the electric field amplitude and phase, respectively.

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Electric Field Amplitude at Exit Plane (ewfd)** in the **Label** text field.

#### *Line Graph 1*

- 1 Right-click **Electric Field Amplitude at Exit Plane (ewfd)** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 From the **Selection** list, choose **Exit Plane**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type `ewfd.Ez`.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type `x`.

- 7 In the **Electric Field Amplitude at Exit Plane (ewfd)** toolbar, click  **Plot**.



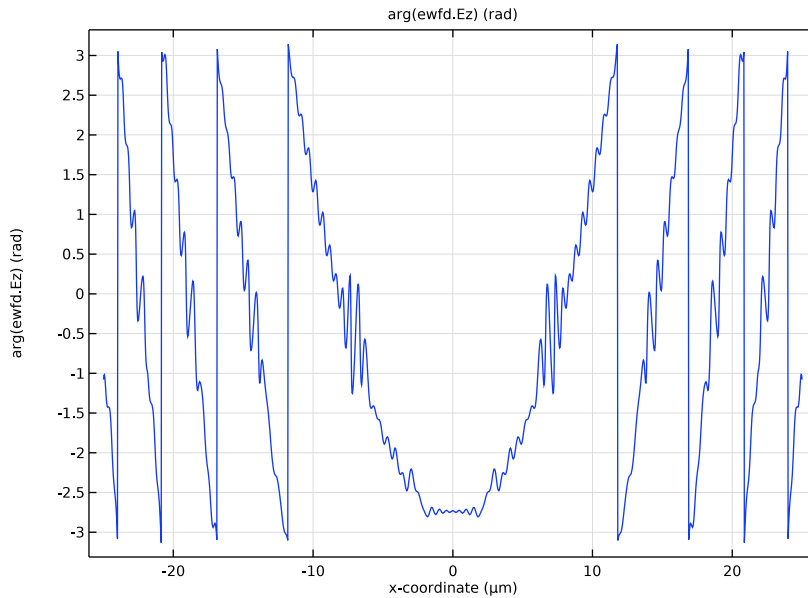
#### *Electric Field Phase at Exit Plane (ewfd)*

- 1 In the **Model Builder** window, right-click **Electric Field Amplitude at Exit Plane (ewfd)** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type **Electric Field Phase at Exit Plane (ewfd)** in the **Label** text field.

#### *Line Graph 1*


- 1 In the **Model Builder** window, expand the **Electric Field Phase at Exit Plane (ewfd)** node, then click **Line Graph 1**.
- 2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type  $\arg(\text{ewfd}.Ez)$ .

4 In the **Electric Field Phase at Exit Plane (ewfd)** toolbar, click  **Plot**.




Now, create a line plot that compares the fields calculated with different, yet equivalent strategies. First by evaluating the Fresnel diffraction integral, then by using the spatial fast Fourier transform postprocessing feature (denoted FFT) and finally by propagating the field from the **Exit Plane** (denoted Helmholtz Equation (ewfd) in the following discussion). For convenience, start by adding all datasets (**Grid ID**, **Cut Line 2D** and **Spatial FFT**) that will be needed later to create the line plot.


#### *Grid ID 1*

- 1 In the **Results** toolbar, click  **More Datasets** and choose **Grid** > **Grid ID**. This dataset defines the destination points for which the Fresnel diffraction integral will be evaluated.
- 2 In the **Settings** window for **Grid ID**, locate the **Parameter Bounds** section.
- 3 In the **Name** text field, type u.
- 4 In the **Minimum** text field, type  $-D/2$ .
- 5 In the **Maximum** text field, type  $D/2$ .

### *Cut Line 2D 1*


- 1 In the **Results** toolbar, click  **Cut Line 2D**. This dataset will constitute the source dataset for the **Spatial FFT** dataset that will be needed to perform the fast Fourier transform.
- 2 In the **Settings** window for **Cut Line 2D**, locate the **Line Data** section.
- 3 In row **Point 1**, set **X** to -25.
- 4 In row **Point 1**, set **Y** to 1.
- 5 In row **Point 2**, set **X** to 25.
- 6 In row **Point 2**, set **Y** to 1.

### *Spatial FFT 1*

- 1 In the **Results** toolbar, click  **More Datasets** and choose **Spatial FFT**.
- 2 In the **Settings** window for **Spatial FFT**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Cut Line 2D 1**.
- 4 Locate the **Transformation** section. Find the **Spatial resolution** subsection. From the **Resolution** list, choose **Manual**.
- 5 Find the **Sampling resolution** subsection. In the  $N_x$  text field, type 256.
- 6 Find the **Spatial layout** subsection. From the **Layout** list, choose **Use zero padding**. This is to increase the sampling points or equivalently the resolution of the Fourier space.
- 7 In the **x padding** text field, type 16384.
- 8 Find the **Fourier space variables** subsection. In the  $f_x$  text field, type  $f_x$ .
- 9 Clear the **Mask DC** checkbox, in order to include the zero-frequency component that is otherwise set to zero by default. In optics, the zero spatial frequency usually corresponds to the center point in the image plane, which we do not want to ignore.

### *Fresnel Versus Helmholtz Comparison*

Now you can create the line plot to compare the results.

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Fresnel Versus Helmholtz Comparison** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Grid ID 1**.

### *Integral Fresnel Approximation*




- 1 Right-click **Fresnel Versus Helmholtz Comparison** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, type **Integral Fresnel Approximation** in the **Label** text field.


- 3 Locate the **y-Axis Data** section. In the **Expression** text field, type  $1/\sqrt{1d\lambda_0*f} * \text{abs}(\text{intop1}(\text{ewfd}.\text{Ez}*\exp(-i*k_0*x^2/(2*f))*\exp(i*2*\pi*\text{dest}(u)*x/(1d\lambda_0*f))))$ .
- 4 Select the **Description** checkbox. In the associated text field, type **Diffraction integral**.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type  $u$ , to express  $u$  in  $\mu\text{m}$ .
- 7 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 8 Find the **Include** subsection. Select the **Label** checkbox.
- 9 Clear the **Solution** checkbox.

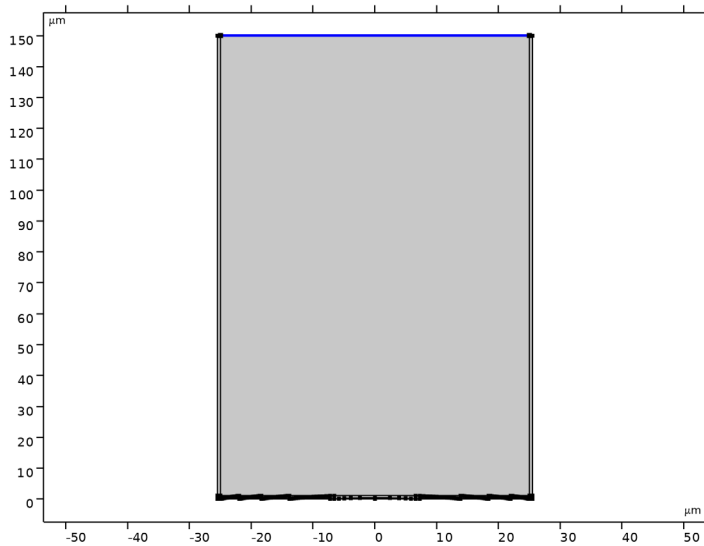
#### *FFT Fresnel Approximation*

- 1 In the **Model Builder** window, right-click **Fresnel Versus Helmholtz Comparison** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, type **FFT Fresnel Approximation** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Spatial FFT I**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type  $1/\sqrt{1d\lambda_0*f} * \text{abs}(\text{fft}(\text{ewfd}.\text{Ez}*\exp(-i*k_0*x^2/(2*f)) )) * D/Nx$ .
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type  $f_x * 1d\lambda_0 * f$ . The x-axis data, the spatial frequency  $f_x$ , needs to be scaled by a factor equal to the product of the wavelength and the focal length.
- 7 Locate the **Legends** section. Select the **Show legends** checkbox.
- 8 Find the **Include** subsection. Select the **Label** checkbox.
- 9 Clear the **Solution** checkbox.

#### *Helmholtz Equation (ewfd)*

- 1 Right-click **Fresnel Versus Helmholtz Comparison** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, type **Helmholtz Equation (ewfd)** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study I/Solution I (sol1)**.
- 4 Locate the **Selection** section. Click to select the  **Activate Selection** toggle button.
- 5 In the **Graphics** window toolbar, click  next to  **Go to Default View**, then choose **Go to View I**.

- 6 Click the  **Zoom Extents** button in the **Graphics** toolbar.
- 7 Select Boundary 12 only. This is the top boundary.



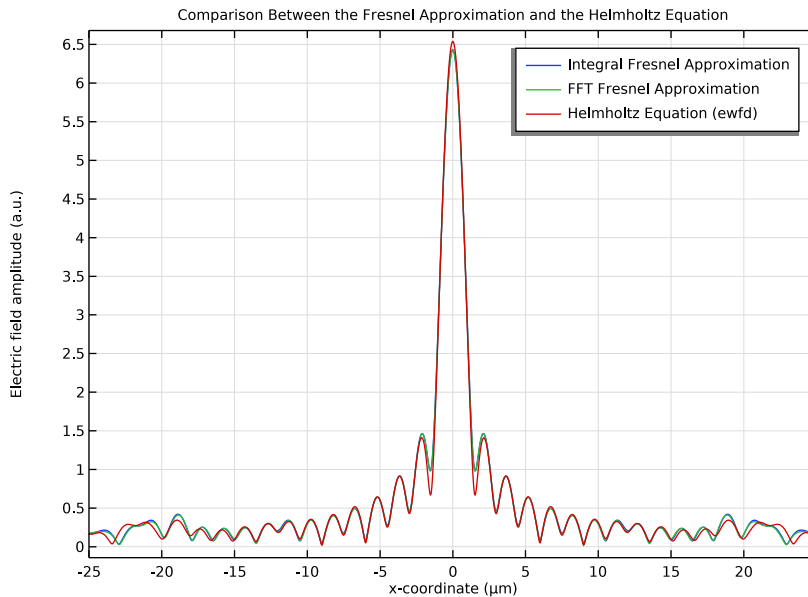
- 8 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 9 In the **Expression** text field, type  $x$ .
- 10 Locate the **Legends** section. Select the **Show legends** checkbox.
- 11 Find the **Include** subsection. Select the **Label** checkbox.
- 12 Clear the **Solution** checkbox.

#### *Fresnel Versus Helmholtz Comparison*

- 1 In the **Model Builder** window, click **Fresnel Versus Helmholtz Comparison**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Plot Settings** section.
- 3 Select the **x-axis label** checkbox. In the associated text field, type  $x$ -coordinate ( $\mu\text{m}$ ).
- 4 Select the **y-axis label** checkbox. In the associated text field, type Electric field amplitude (a.u.).
- 5 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 6 In the **Title** text area, type Comparison Between the Fresnel Approximation and the Helmholtz Equation.
- 7 Locate the **Axis** section. Select the **Manual axis limits** checkbox.
- 8 In the **x minimum** text field, type -25.

9 In the **x maximum** text field, type 25.

10 In the **Fresnel Versus Helmholtz Comparison** toolbar, click  **Plot**.



## ELECTROMAGNETIC WAVES, BEAM ENVELOPES (EWBE)

Now redo the simulation for the Electromagnetic Waves, Beam Envelopes interface.

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Beam Envelopes (ewbe)**.
- 2 In the **Settings** window for **Electromagnetic Waves, Beam Envelopes**, locate the **Components** section.
- 3 From the **Electric field components solved for** list, choose **Out-of-plane vector**.
- 4 Locate the **Wave Vectors** section. From the **Number of directions** list, choose **Unidirectional**.
- 5 Specify the  $\mathbf{k}_1$  vector as

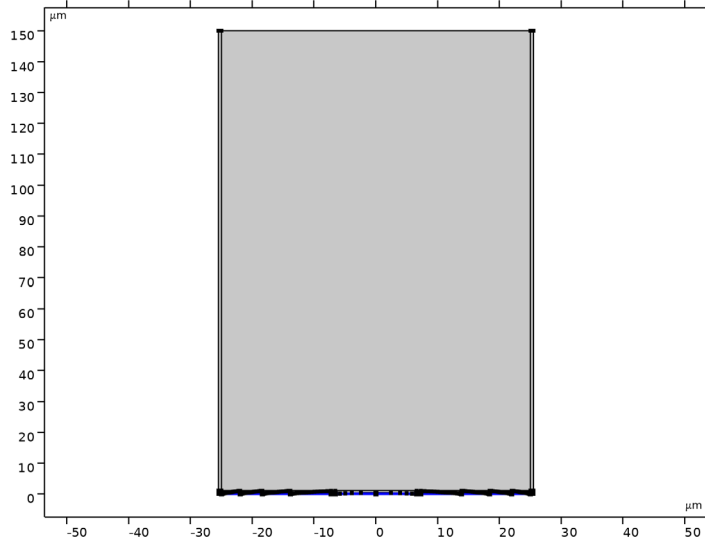
|         |   |
|---------|---|
| 0       | x |
| ewbe.k0 | y |

*Scattering Boundary Condition 1*

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

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

3 From the **Selection** list, choose **Input Plane**.



4 Locate the **Scattering Boundary Condition** section. From the **Incident field** list, choose **Wave given by E field**.

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

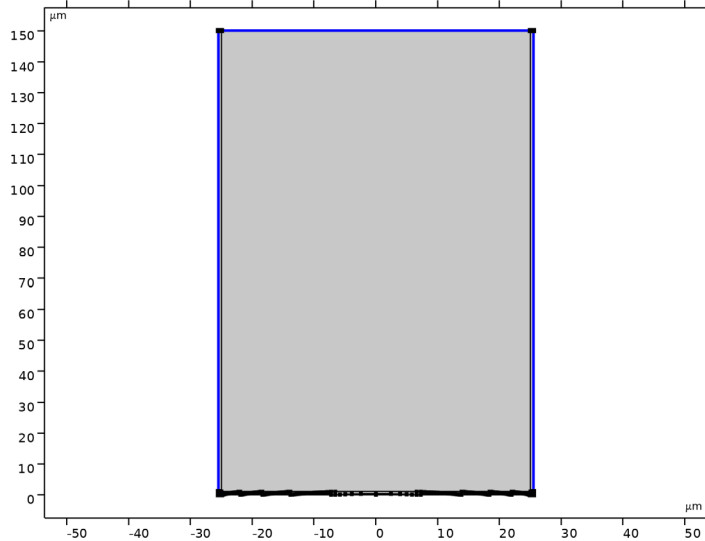
|   |   |
|---|---|
| 0 | x |
| 0 | y |
| 1 | z |

#### *Scattering Boundary Condition 2*

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

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

3 From the **Selection** list, choose **Scattering Boundaries**.



#### **FINE MESH**

Add a second, coarser, mesh that will be used for the simulation with the Electromagnetic Waves, Beam Envelopes interface.

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Fine Mesh** and choose **Duplicate**.

#### **COARSE MESH**

In the **Settings** window for **Mesh**, type Coarse Mesh in the **Label** text field.

*Size 1*

1 In the **Model Builder** window, expand the **Coarse Mesh** node.

2 Right-click **Mapped 1** and choose **Size**.

3 In the **Settings** window for **Size**, locate the **Element Size** section.


4 Click the **Custom** button.

5 Locate the **Element Size Parameters** section.

6 Select the **Maximum element size** checkbox. In the associated text field, type  $2*1da0$ .


#### **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*

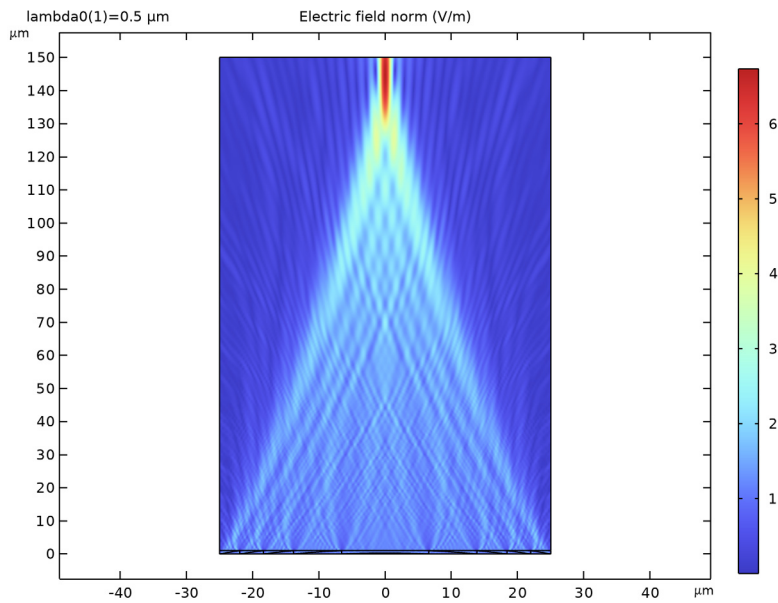
- 1 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.
- 2 In the **Wavelengths** text field, type 1da0.
- 3 In the **Study** toolbar, click  **Compute**.

## RESULTS

### *Electric Field (ewbe)*

- 1 In the **Settings** window for **2D Plot Group**, locate the **Plot Settings** section.
- 2 From the **View** list, choose **View 1**.

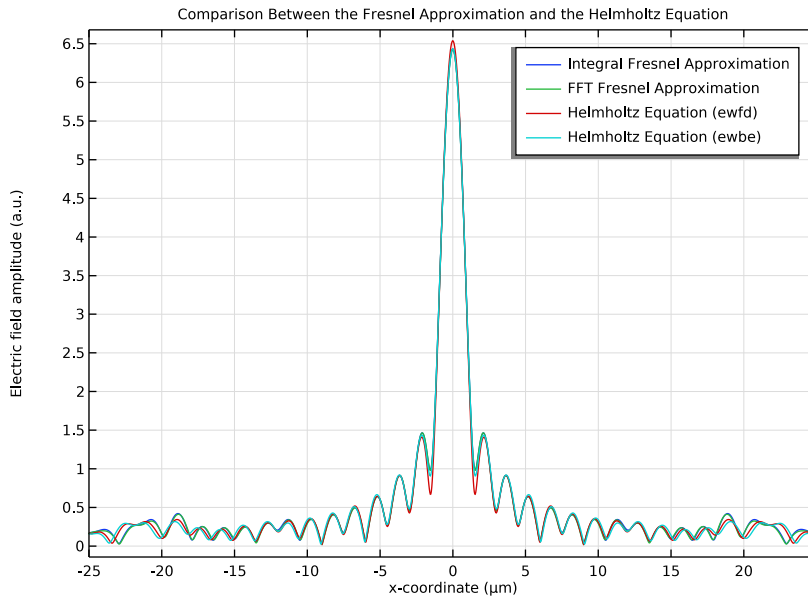
- 3 Click the  **Zoom Extents** button in the **Graphics** toolbar.



*Helmholtz Equation (ewbe)*

- 1 In the **Model Builder** window, right-click **Helmholtz Equation (ewfd)** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, type Helmholtz Equation (ewbe) in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type `ewbe.normE`.

5 In the **Fresnel Versus Helmholtz Comparison** toolbar, click  **Plot**.




The comparison is excellent also with the Electromagnetic Waves, Beam Envelopes interface. Moreover, the simulation time is much shorter, as the Electromagnetic Waves, Beam Envelopes interface can be performed with a much coarser mesh.

### *Creating and Running a Model Method*

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#### **NEW METHOD**

The last part of this instruction shows how to implement a Model Method. If you change the parameter  $M$ , the number of discretization levels, you need to change the number of points in the polygon in the **Fresnel Lens Zone** geometry part. However, once you have created the Model Method, you can call the Model Method from the GUI to automatically rebuild the geometry part and the geometry. You can only create and edit the Model Method using Windows, but you can run it from both Linux and Mac.

- 1 In the **Developer** toolbar, click  **New Method**.
- 2 In the **New Method** dialog, type `rebuildGeometry` in the **Name** text field.
- 3 Click **OK**.

## APPLICATION BUILDER

### *rebuildGeometry*

1 In the **Application Builder** window, under **Methods** click **rebuildGeometry**.

2 Copy the following code into the **rebuildGeometry** window:

```
// This method clears the coordinates in the Fresnel Lens Zone geometry parts
// and then calculates new coordinates

GeomSequence gs = model.geom("part1");
ModelParam modelParam = gs.localParam();

// Remove all local parameters, except the Digitization count for zone parameter,
Mi

for (String name : modelParam.varnames())
    if (!"Mi".equals(name))
        modelParam.remove(name);

// Read the digitization count parameter and generate local x-coordinate
parameters
int digitizationLevelCount = (int) model.param().evaluate("M");
for (int i = 0; i < digitizationLevelCount+1; i++) {
    String param = "x"+i;
    if (i == 0)
        modelParam.set(param, "if(zone > 1,sqrt(R^2-(R-(sag-(N+1-zone)*d))^2),0)",
"Left end of zone");
    else if (i == digitizationLevelCount)
        modelParam.set(param, "sqrt(R^2-(R-(sag-(N-zone)*d))^2)", "Right end of
zone");
    else {
        String paramOrder;
        if (i == 1)
            paramOrder = "1st";
        else if (i == 2)
            paramOrder = "2nd";
        else if (i == 3)
            paramOrder = "3rd";
        else
            paramOrder = "+i+th";
        modelParam.set(param, "sqrt(R^2-(z0+(N-zone+1)*d-(M-Mi+"+i+"*dm)^2)",
paramOrder+" step right end");
    }
}

// Generate local y-coordinate parameters
for (int i = 0; i < digitizationLevelCount+1; i++) {
    String param = "y"+i;
    if (i == 0)
        modelParam.set(param, "-dm", "Base level");
    else {
        String paramOrder;
        if (i == 1)
            paramOrder = "1st";
```

```

        else if (i == 2)
            paramOrder = "2nd";
        else if (i == 3)
            paramOrder = "3rd";
        else
            paramOrder = ""+i+"th";
        modelParam.set(param, "(M"+i+")*dm", paramOrder+" level");
    }
}

// Set the new coordinate vectors for the polygon
String xCoordinates = "";
String yCoordinates = "";
for (int i = 0; i < digitizationLevelCount+1; i++) {
    xCoordinates += "x"+i+" "+x"+i+(i < digitizationLevelCount ? " " : "");
    yCoordinates += "y"+i+" "+y"+(i < digitizationLevelCount ? (i+1)+" " : "0");
}


GeomFeature polygon = gs.feature("pol1");
polygon.set("x", xCoordinates);
polygon.set("y", yCoordinates);

// Recreate the geometry
model.component("comp1").geom("geom1").run();

```

Now, go back to the **Model Builder**, change the digitization count parameter M, and then run the new model method.

## METHODS

In the **Home** toolbar, click  **Model Builder**.

## 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        |
|------|------------|-------|--------------------|
| M    | 8          | 8     | Digitization level |

- 4 In the **Home** toolbar, click  **Run Method** and choose **rebuildGeometry**.

## DEFINITIONS



Verify that the structure now is using eight steps per zone.


*Hide for Physics I*

In the **Model Builder** window, under **Component 1 (comp1) > Definitions > View 3** right-click **Hide for Physics I** and choose **Enable**.

*Exit Plane*

**1** In the **Model Builder** window, under **Component 1 (comp1) > Definitions > Selections** click **Exit Plane**.

**2** In the **Settings** window for **Explicit**, in the **Graphics** window toolbar, click  next to  **Go to Default View**, then choose **Go to View 3**.

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

