Model created in COMSOL Multiphysics 6.4

Modeling a Scatterer Near an Optical Waveguide

Introduction

The dielectric slab waveguide is one of the conceptual building blocks in photonic structure design. Although most real structures are more complex than just a two-dimensional dielectric slab, a two-dimensional model permits to simplify the analysis. This model simulates the case of a small lossy scatterer in the proximity of an optical waveguide, shows how it interacts with the fields, and calculates reflection and transmission along the waveguide, as well as losses and scattering.

Model Definition

The schematic of the structure is shown in Figure 1. A dielectric slab waveguide has a small circular metallic object located nearby. The scatterer interacts with the fields, thus leading to some losses within the material, and causing scattering of light into all directions. In the absence of the nearby object, this example would reduce to a perfect dielectric slab waveguide (see the Application Library model Dielectric Slab Waveguide).

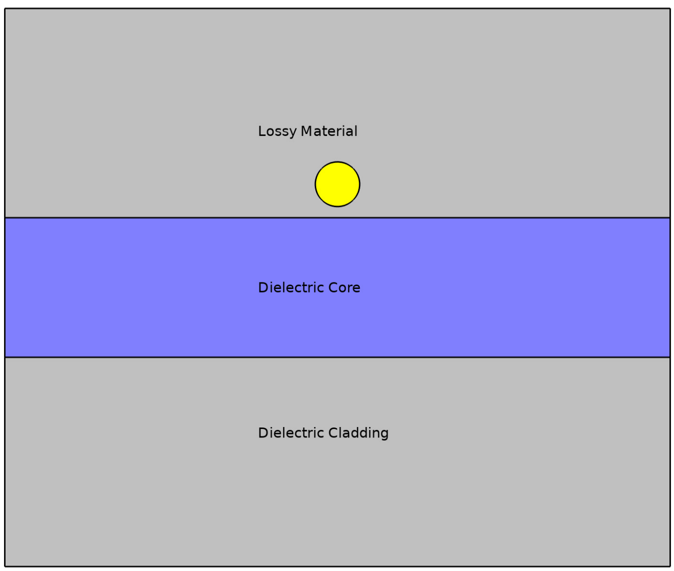


Figure 1: Schematic of a 2D dielectric slab waveguide with a lossy material in proximity to the core.

Imagine a waveguide that is wide enough to support multiple modes. For the sake of simplicity, this model restricts the analysis to just the example of the electric field polarized out of the modeling plane. Assume that either the electric or magnetic field is polarized purely out of plane and that there is no coupling between these two as long as all materials are isotropic.

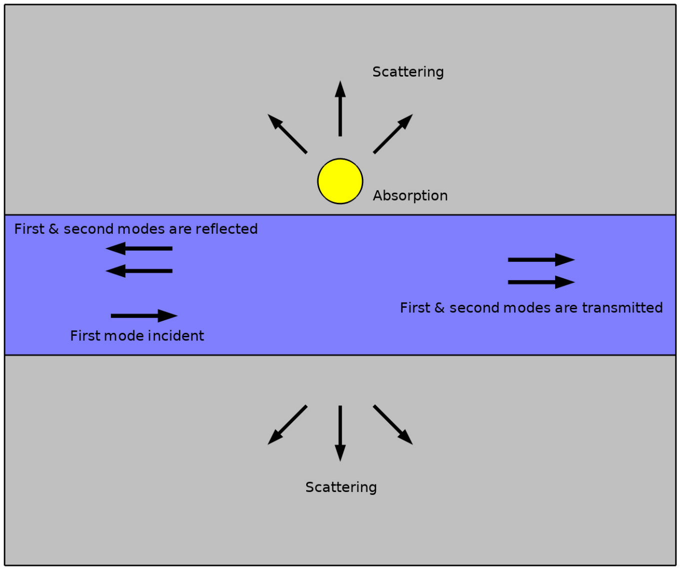


Figure 2: The incident light guided along the waveguide can be reflected, transmitted, absorbed, and scattered.

The reflection and transmission along the waveguide, as well as absorption and scattering mechanisms are shown in Figure 2. Here, light propagates along the waveguide toward the scatterer (from left to right), and this incident light is the first or fundamental mode. Due to the presence of the scatterer, some fraction of the incident light will be

1 transmitted forward and of the same fundamental mode,
2 transmitted forward, but converted into the second mode,
3 reflected backward and of the same fundamental mode,
4 reflected backward, and converted into the second mode,
5 absorbed by the lossy metallic inclusion, and
6 scattered into other directions.

Computation of transmission into the four possible guided modes of the waveguide (items 1–6) requires four different numerical ports into the model, two on each side. As already discussed in Ref. 1, it is possible to introduce multiple interior slit port boundary conditions at boundaries within the modeling space. Modeling the absorption into the lossy material simply involves integrating the loss within the metallic object.

In summary, this model simulates a dielectric slab waveguide with a lossy scatterer nearby to analyze the guided light, reflection, transmission, absorption, and scattering mechanisms in 2D using the Electromagnetic Waves, Frequency Domain (ewfd) interface. Numeric ports are used and perfectly matched layers are employed to absorb most of the outgoing radiation. A Frequency Domain and four Boundary Mode Analysis study steps are applied to solve the domain fields.

Results and Discussion

Figure 3 shows the electric field norm from the simulation. The numeric port boundary condition at the left excites a fundamental mode that propagates in the tangential direction.

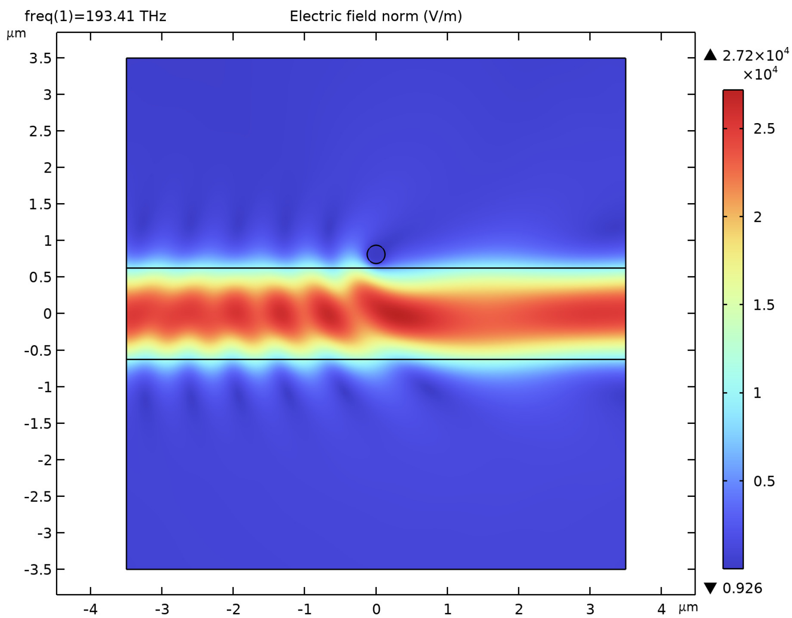


Figure 3: The Electric field norm.

Figure 4 shows the total resistive losses within the scatterer. Here, the loss distribution is not uniform within the material. Maximum losses are observed at the bottom part of the scatterer which is closer to the waveguide.

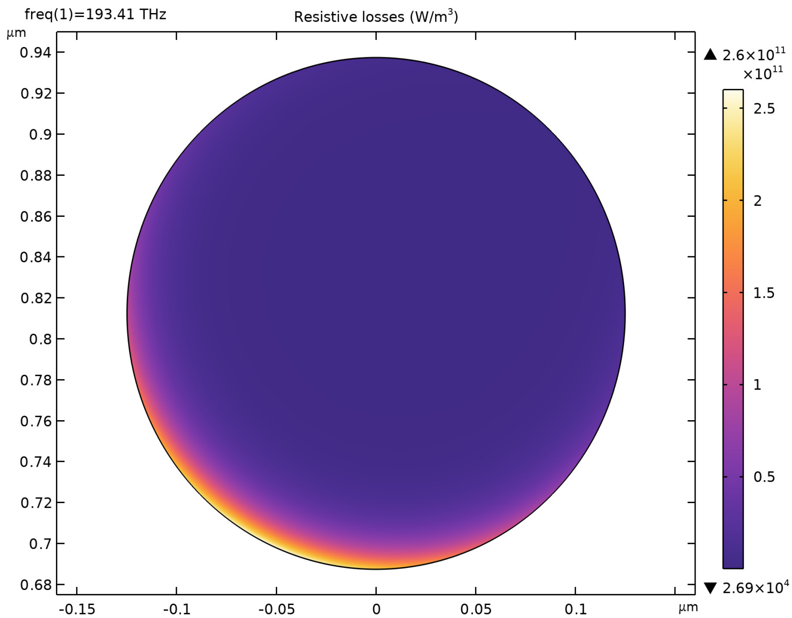


Figure 4: Resistive losses in the lossy scatterer.

For further details, see the blog post in Ref. 2.

References

1. Walter Frei, "Modeling Waveguides that Support Multiple Modes," COMSOL Blog, Aug. 12, 2020; www.comsol.com/blogs/modeling-waveguides-that-support-multiple-modes/.

2. Walter Frei, "Modeling a Scatterer Near an Optical Waveguide," COMSOL Blog, Aug. 25, 2020; www.comsol.com/blogs/modeling-a-scatterer-near-an-optical-waveguide/.

Application Library path: `Wave_Optics_Module/Waveguides/waveguide_with_scatterer`

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 **2D**.

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 **General Studies** > **Frequency Domain**.

6 Click **Done**.

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**.

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
lda0	1550[nm]	1.55E-6 m	Wavelength
n_core	1.5	1.5	Refractive index, core
n_cladding	1	1	Refractive index, cladding
h_core	1.25[um]	1.25E-6 m	Thickness, core, section A
h_cladding	8[um]	8E-6 m	Thickness, cladding
L_core	8[um]	8E-6 m	Core length

Name	Expression	Value	Description
f0	c_const/lda0	1.9341E14 1/s	Frequency
t_PML	0.5[um]	5E-7 m	PML thickness
Pin	1[W/m]	1 W/m	Power in

GEOMETRY 1

The geometry consists of a slab waveguide, with a scatterer on top, embedded in a cladding material.

Rectangle 1 (r1)

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

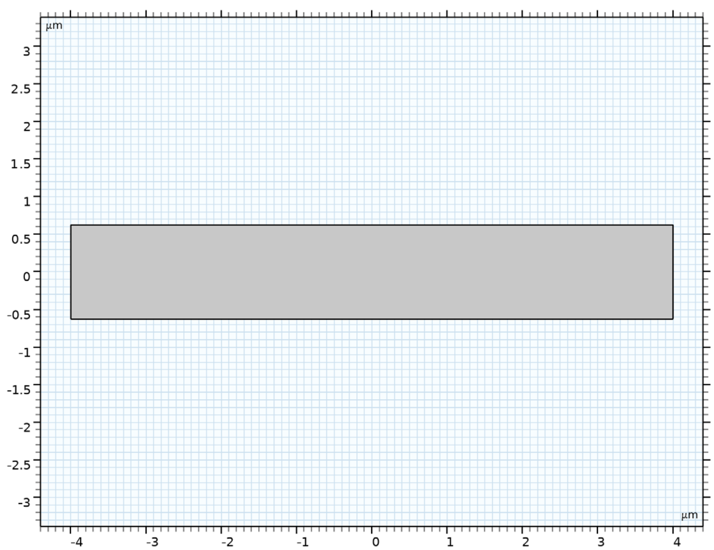
2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type L_core.

4 In the **Height** text field, type h_core.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 Click **Build Selected**.



Rectangle 2 (r2)

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 L_core.

4 In the **Height** text field, type `h_cladding`.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

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

Layer name	Thickness (µm)
`Layer 1`	`t_PML`

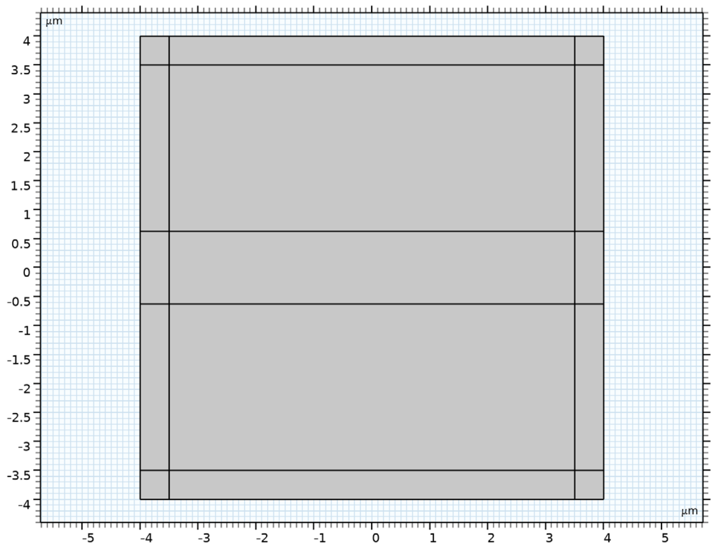
7 Select the **Layers to the left** checkbox.

8 Select the **Layers to the right** checkbox.

9 Select the **Layers on top** checkbox.

10 Click **Build Selected**.

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



Circle 1 (c1)

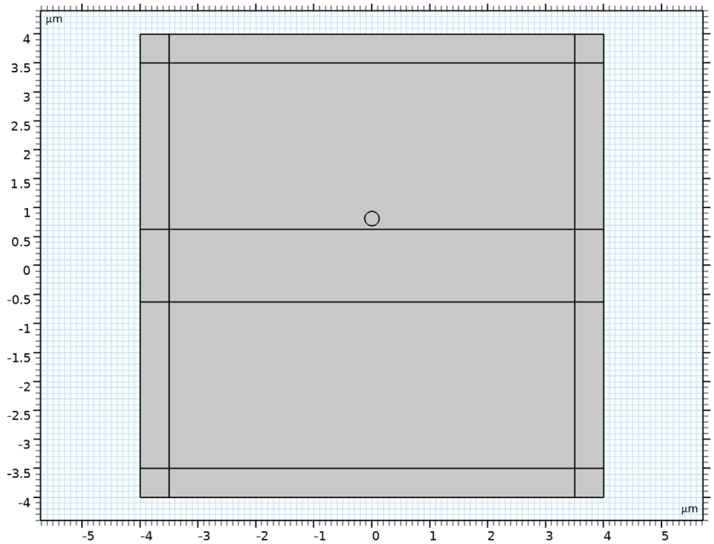
1 In the **Geometry** toolbar, click **Circle**.

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

3 In the **Radius** text field, type `h_core/10`.

4 Locate the **Position** section. In the **y** text field, type `h_core*0.65`.

5 Click **Build All Objects**.



MATERIALS

Cladding

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 `Cladding` in the **Label** text field.

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

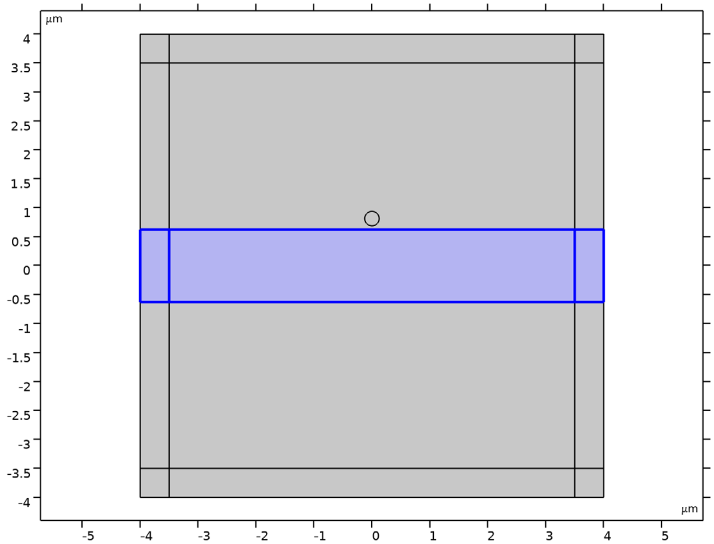
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_cladding`	1	Refractive index

Core

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

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

3 Select Domains 3, 8, and 13 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_core	1	Refractive index

ADD MATERIAL

Pick gold as the lossy scatterer from the Optical material library.

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 **Optical** > **Inorganic Materials** > **Au - Gold** > **Experimental data: bulk, thick film** > **Au (Gold) (Johnson and Christy 1972: n,k 0.188-1.937 um)**.

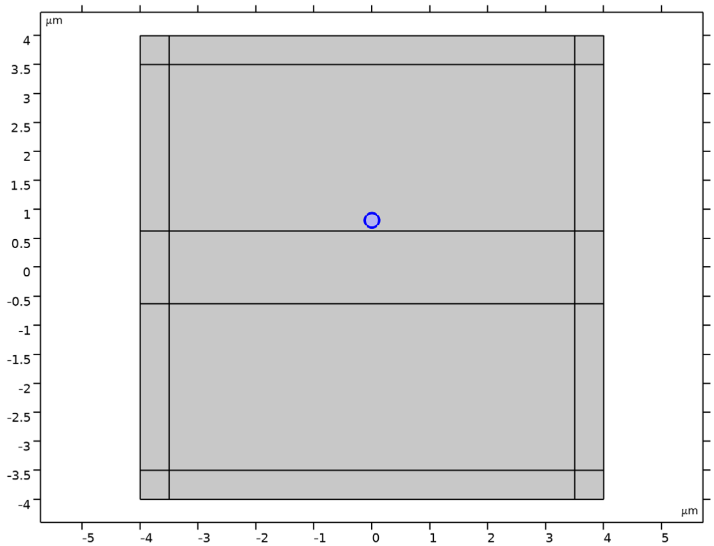
4 Right-click and choose **Add to Component 1 (comp1)**.

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

MATERIALS

Au (Gold) (Johnson and Christy 1972: n,k 0.188-1.937 um) (mat3)

Select Domain 16 only.

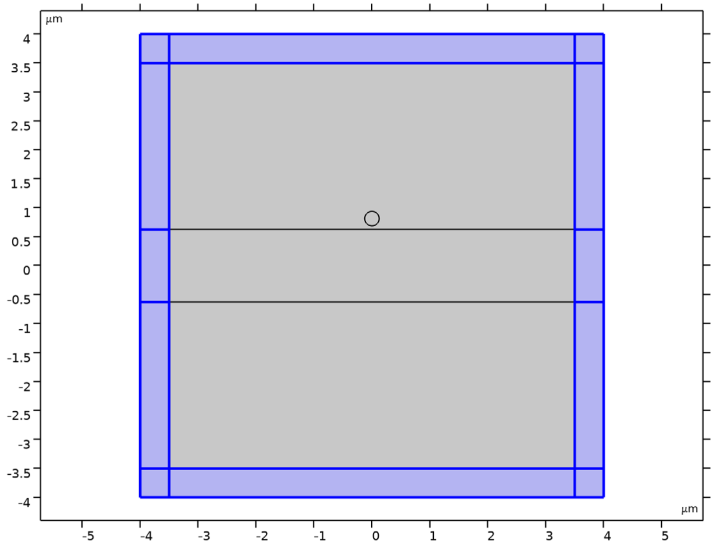


DEFINITIONS

Perfectly Matched Layer 1 (pml1)

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

2 Select Domains 1–6 and 10–15 only.



ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Define the incident port.

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**.

Port 1

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

2 Select Boundaries 14, 16, and 18 only.

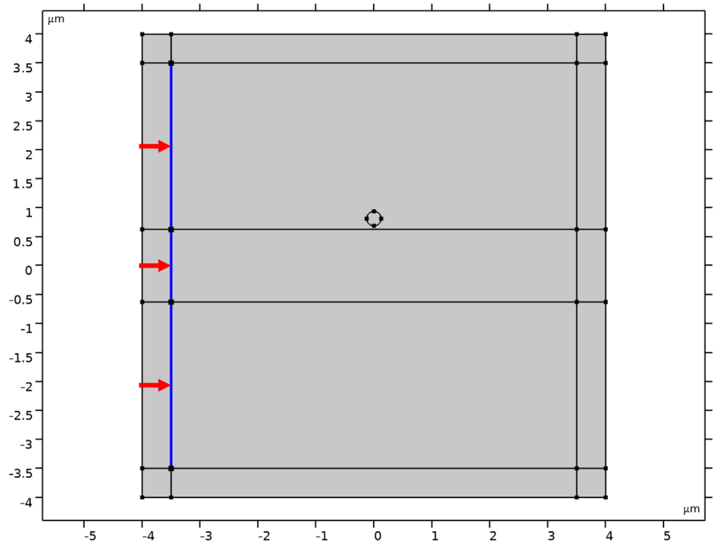
3 In the **Settings** window for **Port**, locate the **Port Properties** section.

4 From the **Type of port** list, choose **Numeric**.

5 In the P_{in} text field, type `Pin`.

6 Select the **Activate slit condition on interior port** checkbox.

7 Click **Toggle Power Flow Direction**.



Port 2

Define the transmission port for the first mode.

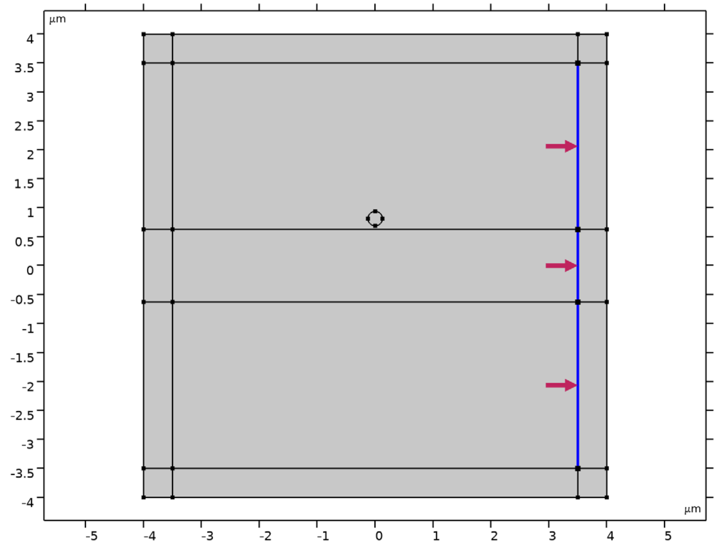
1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 Select Boundaries 25, 27, and 29 only.

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

4 From the **Type of port** list, choose **Numeric**.

5 Select the **Activate slit condition on interior port** checkbox.



Port 3

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

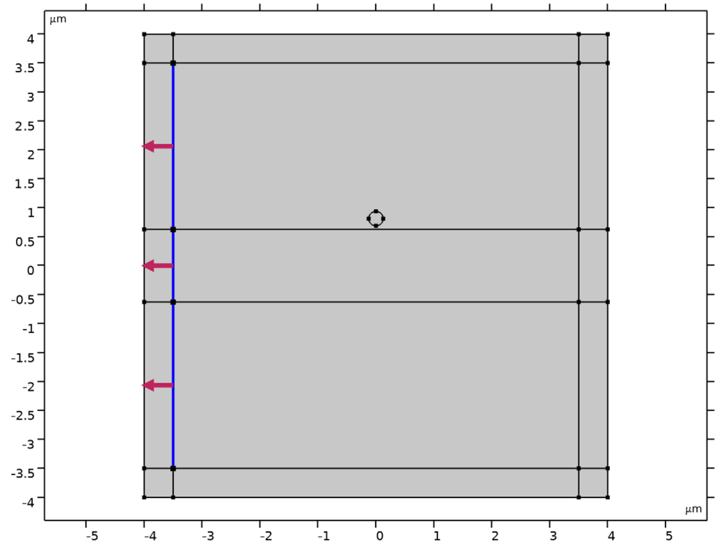
Define the port to capture the first and second reflected modes.

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

3 Click  **Clear Selection**.

4 Select Boundaries 14, 16, and 18 only.

5 Locate the **Port Properties** section. Click **Toggle Power Flow Direction**.



Port 4

1 Right-click **Port 3** and choose **Duplicate**.

Define the transmission port for the second mode.

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

3 Click **Clear Selection**.

4 Select Boundaries 25, 27, and 29 only.

5 Locate the **Port Properties** section. Click **Toggle Power Flow Direction**. These boundaries are same as Port 2.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Electromagnetic Waves, Frequency Domain (ewfd)** section.

3 Select the **Resolve wave in lossy media** checkbox.

STUDY 1

Step 1: Frequency Domain

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

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

3 In the **Frequencies** text field, type `f0`.

Step 2: Boundary Mode Analysis

1 In the **Study** toolbar, click **More Study Steps** and choose **Other** > **Boundary Mode Analysis**.

2 In the **Settings** window for **Boundary Mode Analysis**, locate the **Study Settings** section.

3 In the **Mode analysis frequency** text field, type `f0`.

4 In the **Search for modes around shift** text field, type `n_core`.

Step 3: Boundary Mode Analysis 1

1 Right-click **Step 2: Boundary Mode Analysis** and choose **Duplicate**.

2 In the **Settings** window for **Boundary Mode Analysis**, locate the **Study Settings** section.

3 In the **Port name** text field, type `2`.

Step 4: Boundary Mode Analysis 2

1 Right-click **Step 3: Boundary Mode Analysis 1** and choose **Duplicate**.

2 In the **Settings** window for **Boundary Mode Analysis**, locate the **Study Settings** section.

3 In the **Port name** text field, type `3`.

4 Select the **Desired number of modes** checkbox. In the associated text field, type `2`.

Step 5: Boundary Mode Analysis 3

1 Right-click **Step 4: Boundary Mode Analysis 2** and choose **Duplicate**.

2 In the **Settings** window for **Boundary Mode Analysis**, locate the **Study Settings** section.

3 In the **Port name** text field, type `4`.

Step 1: Frequency Domain

1 In the **Model Builder** window, click **Step 1: Frequency Domain**.

2 Drag and drop below **Step 4: Boundary Mode Analysis 3**.

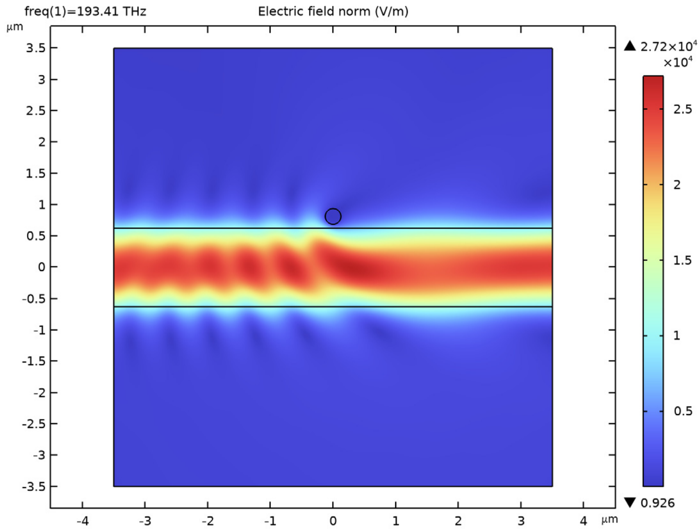
3 In the **Study** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd)

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

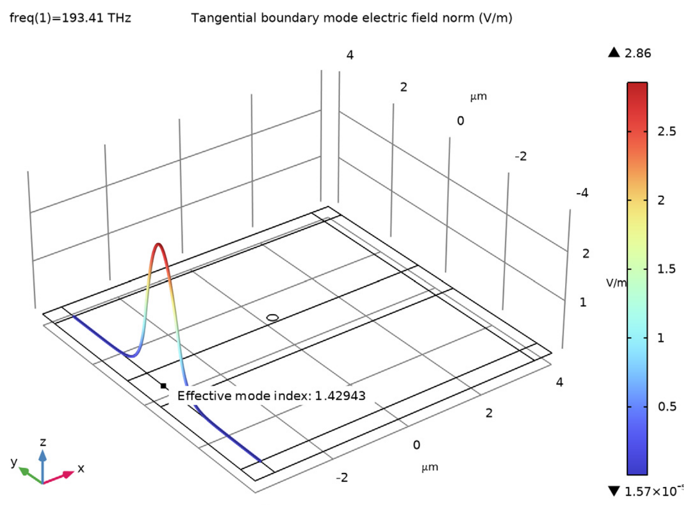
2 Click the **Zoom Extents** button in the **Graphics** toolbar.



Electric Mode Field, Port 1 (ewfd)

Plot the first mode at port 1.

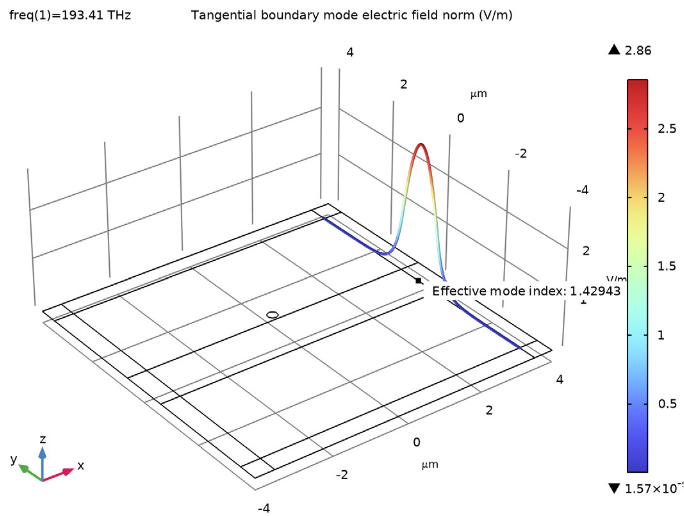
In the **Model Builder** window, click **Electric Mode Field, Port 1 (ewfd)**.



Electric Mode Field, Port 2 (ewfd)

Plot the first mode at port 2.

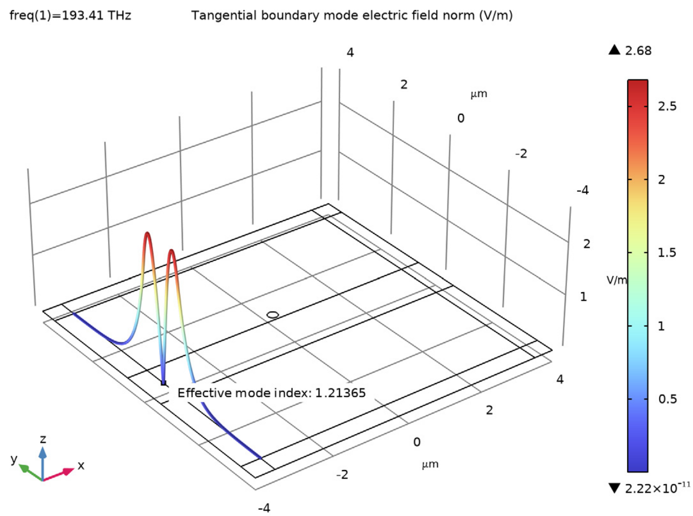
In the **Model Builder** window, click **Electric Mode Field, Port 2 (ewfd)**.



Electric Mode Field, Port 3 (ewfd)

Plot the second mode at port 1.

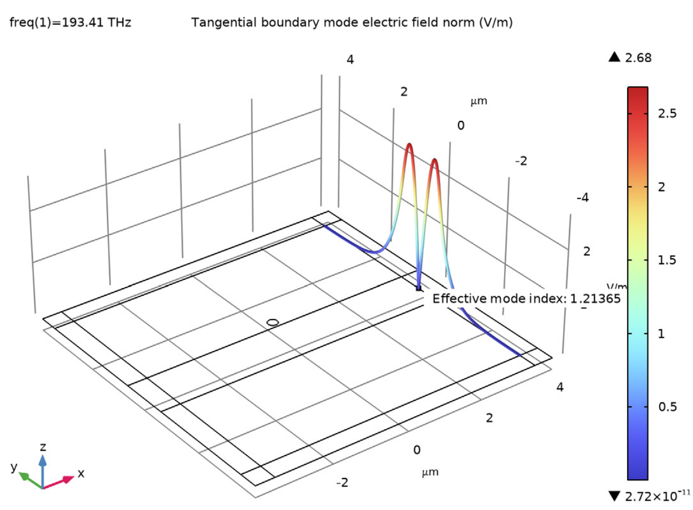
In the **Model Builder** window, click **Electric Mode Field, Port 3 (ewfd)**.



Electric Mode Field, Port 4 (ewfd)

Plot the second mode at port 2.

In the **Model Builder** window, click **Electric Mode Field, Port 4 (ewfd)**.



Electric Field (ewfd)

Plot the resistive losses in the gold scatterer.

Losses

1 In the **Model Builder** window, right-click **Electric Field (ewfd)** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Losses` in the **Label** text field.

3 Click to expand the **Selection** section. Click **Clear Selection**.

4 Select Domain 16 only.

Surface 1

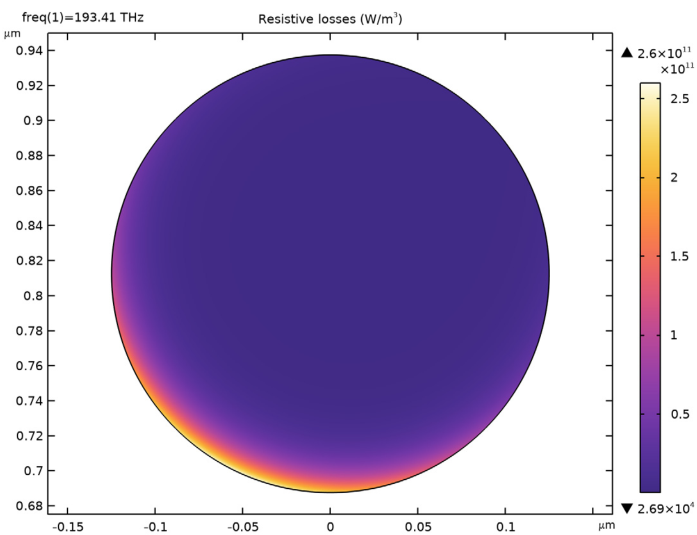
1 In the **Model Builder** window, expand the **Losses** node, then click **Surface 1**.

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

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

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

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



Reflectance, Transmittance, and Loss (ewfd)

As the total absorptance variable, `ewfd.Atotal`, only includes the loss due to absorption in the Gold domain, add a variable accounting for the loss due to power flowing into the top and bottom PML domains and for radiation not matching the port mode fields, `ewfd.Lsca`.

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

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

Reflectance, Transmittance, and Loss (ewfd)

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

2 In the **Settings** window for **Global Evaluation**, type `Reflectance, Transmittance, and Loss (ewfd)` in the **Label** text field.

3 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Heating and losses** > **ewfd.Lsca - Scattering loss - 1**.

4 In the **Reflectance, Transmittance, and Loss (ewfd)** toolbar, click **Evaluate**.

Loss Calculation

Also add a separate **Global Evaluation** node to separately calculate the absorptance, scattering, and total loss.

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

2 In the **Settings** window for **Global Evaluation**, type `Loss Calculation` in the **Label** text field.

3 Click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Heating and losses** > **ewfd.Atotal - Absorptance - 1**.

4 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Electromagnetic Waves, Frequency Domain** > **Heating and losses** > **ewfd.Lsca - Scattering loss - 1**.

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

Expression	Unit	Description
ewfd.Atotal+ewfd.Lsca	1	Total losses

6 Click **Evaluate**.