Created in COMSOL Multiphysics 6.2

Single-Bit Hologram

Introduction

A hologram is a holographically recorded object. When two coherent light beams intersect each other, an interference pattern is generated. If this occurs in a material that is sensitive to light intensities greater than a certain exposure threshold, the interference pattern is recorded in the material as a modulation of the refractive index. Such a material is called a holographic material and the process of recording is called holographic recording. When one of the two light beams is originally scattered by an object before entering the holographic material, the beam is called the object beam while the other beam is called the reference beam. In this case, the recorded hologram also contains the information about the scattering object. Now, if the hologram is illuminated by the reference beam alone in the same optical setup, the object beam will be regenerated from the holographic material. This process is called the holographic retrieval. This concept is depicted in Figure 1.

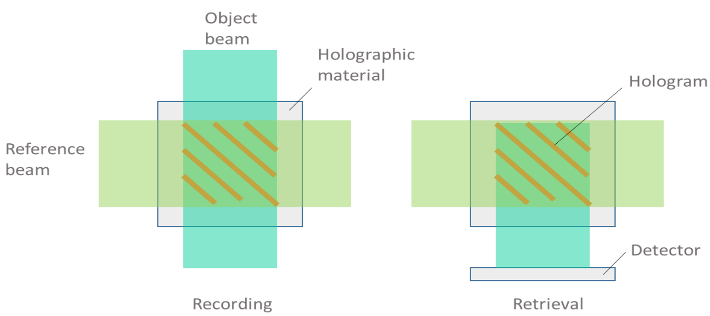


Figure 1: Holographic recording and retrieval.

Model Definition

In this model, the simplest example is chosen, in which the object beam has the same profile as the reference beam. The reference beam enters a holographic material from the left boundary while the object beam enters it from the top boundary. In the recording process, the two beams cross at 90 degree angle in the material and make interference fringes tilted at 45 degrees. For intensities above a certain exposure threshold, a refractive index modulation is induced in the holographic material on top of the constant background refractive index. In the retrieval, only the reference beam illuminates the hologram. Then this beam is partially transmitted and partially reflected off by the hologram, which regenerates the object beam. You can say that the hologram is working as a volume Bragg grating satisfying the Bragg condition for the reference beam.

Results and Discussion

Figure 2 shows the electric field distribution during the recording phase. Notice that the intensity pattern in the rightmost figure shows diagonal stripes that result in the striped refractive index modulation, shown in Figure 3

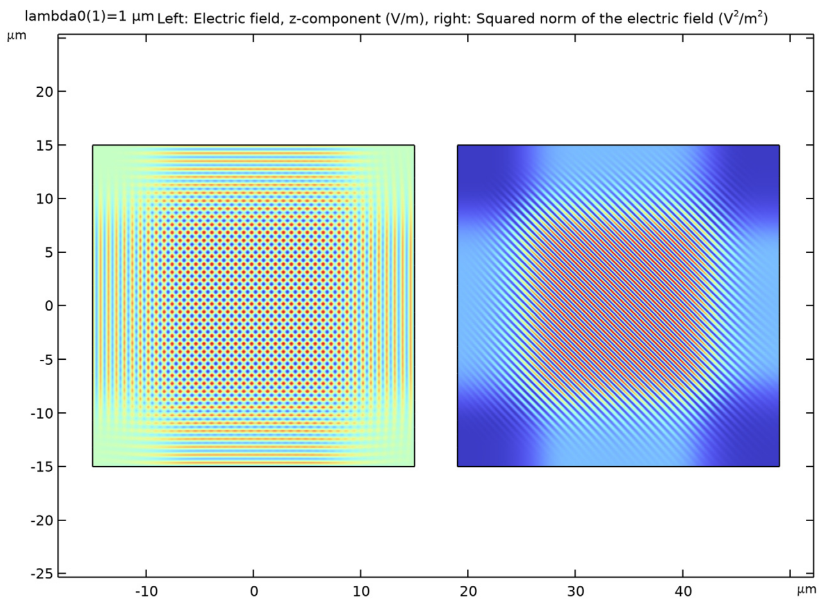


Figure 2: Electric field distribution during recording. The left figure show the z-component of the electric field, whereas the right figure shows the squared norm of the electric field.

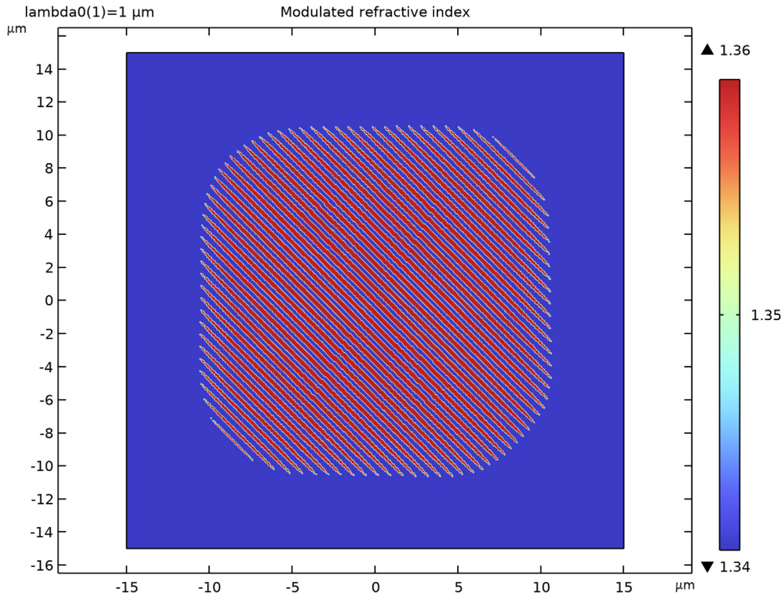


Figure 3: The refractive index distribution.

Figure 4 shows the intensity distribution across a cross section of the beam. The red line indicates the exposure threshold level for the holographic material. Notice that the refractive index modulation in Figure 5 starts at the location where the threshold level intersects the intensity distribution. In the wings of the beam, the intensity level is too low to induce any refractive index modulation.

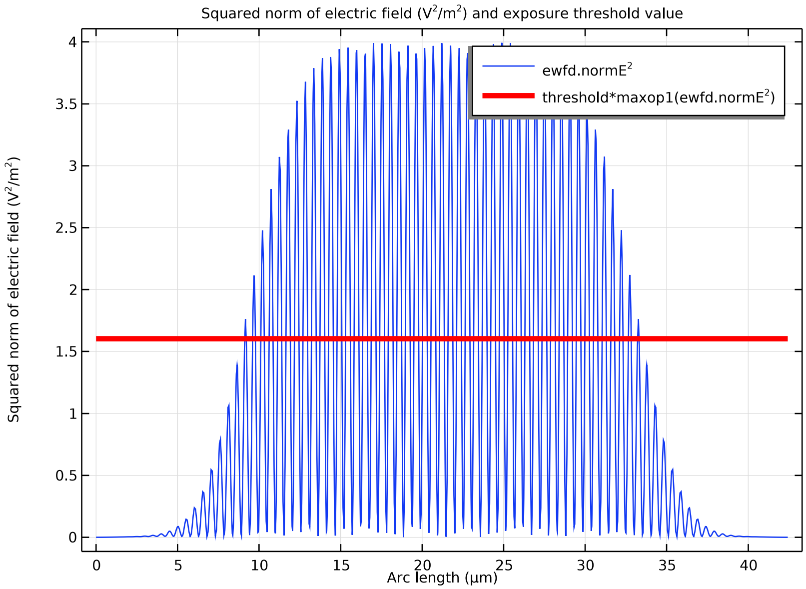


Figure 4: The electric field distribution during recording. The blue curve shows the squared electric field norm, whereas the red line indicates the exposure threshold for the holographic material.

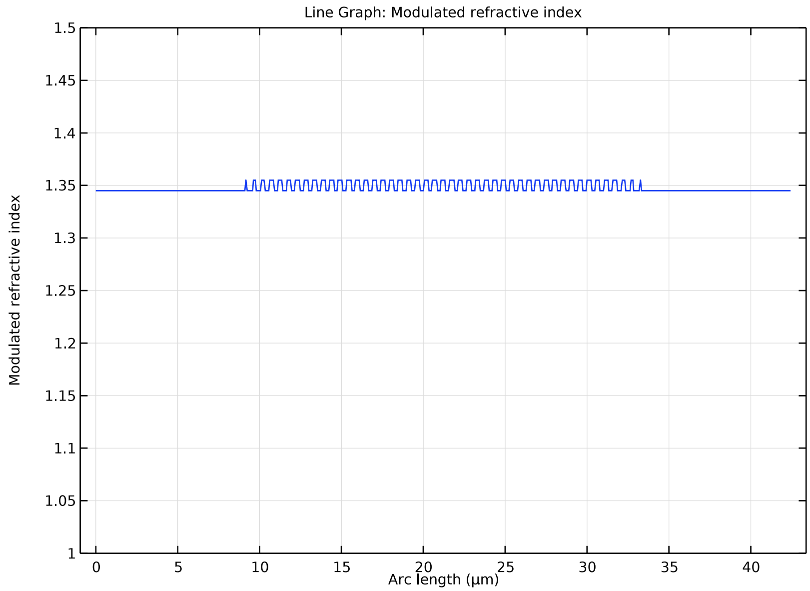


Figure 5: The induced refractive index modulation.

Finally, Figure 6 shows the electric field distribution during the retrieval phase. Here, only the reference beam is incident. However, as it is scattered by the induced refractive index grating, the object beam is regenerated and propagates toward the bottom of the figure.

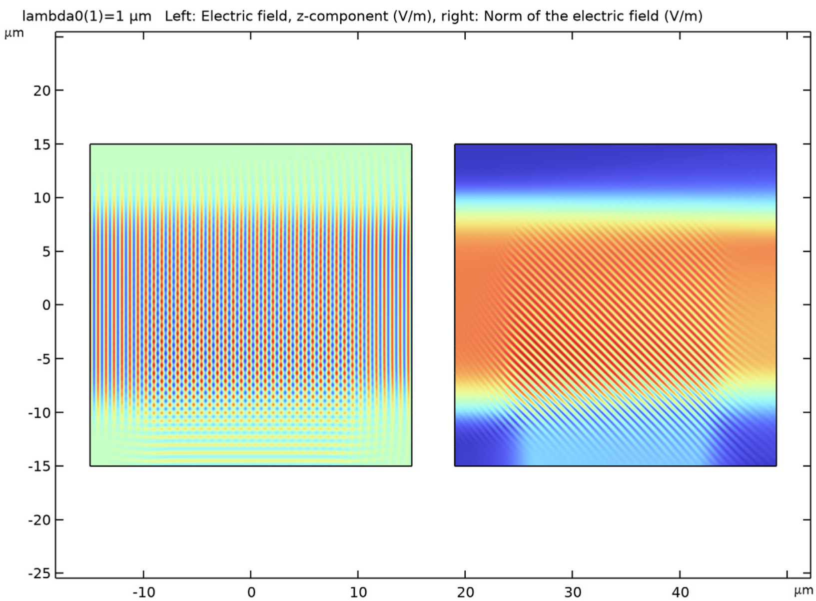


Figure 6: The electric field distribution during the retrieval phase. The left figure shows the z-component of the electric field, whereas the right figure shows the norm of the electric field.

Application Library path: `Wave_Optics_Module/Gratings_and_Metamaterials/single_bit_hologram`

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 **Preset Studies for Selected Physics Interfaces> Wavelength Domain**.

6 Click **Done**.

GLOBAL DEFINITIONS

Start by loading the parameters that defines the model geometry and material properties.

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 `single_bit_hologram_parameters.txt`.

GEOMETRY 1

The simulation domain consists of a rectangle with width `L` and height `H`.

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**.

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`.

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

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

6 Click **Build All Objects**.

MATERIALS

Material 1 (mat1)

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

2 In the **Settings** window for **Material**, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	n1	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

DEFINITIONS

A maximum operator will be used later when defining the refractive index variation of the hologram.

Maximum 1 (maxop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Maximum**.

2 Select Domain 1 only.

Refractive Index During Recording

Now, define the refractive indices that will be used for the recording phase and the retrieval phase. This variable will later define the refractive index for the material. In the study steps, you later define which of the two refractive index variables that will be used for the different phases.

1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Refractive Index During Recording` in the **Label** text field.

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

Name	Expression	Unit	Description
n	n1		Background refractive index

4 Right-click **Refractive Index During Recording** and choose **Duplicate**.

Modulated Refractive Index

1 In the **Model Builder** window, under **Component 1 (comp1)>Definitions** click **Refractive Index During Recording 1**.

2 In the **Settings** window for **Variables**, type `Modulated Refractive Index` in the **Label** text field.

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

Name	Expression	Unit	Description
`n_mod`	`n1+dn*(((ewfd.normE/maxop1(ewfd.normE))^2>threshold)-0.5)`		`Modulated refractive index`

Refractive Index During Retrieval

1 In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Refractive Index During Retrieval` in the **Label** text field.

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

Name	Expression	Unit	Description
`n`	`withsol('sol2',n1+dn*(((ewfd.normE/maxop1(ewfd.normE))^2>threshold)-0.5))`		`Background refractive index`

The `withsol` operator allows you to use expressions from a previous solution. In this case, it is the solution from the first study step, here denoted `sol2`, that will be used for defining the refractive index distribution during the second study step.

MATERIALS

Material 1 (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Material 1 (mat1)**.

2 In the **Settings** window for **Material**, locate the **Material Contents** section.

3 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	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

As the same study will include both the study step for the recording of the hologram and the study step for the retrieval of the object beam, all features required for both study steps will be added to the physics in the next step. Later on, the physics trees will be modified in the study step settings.

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.

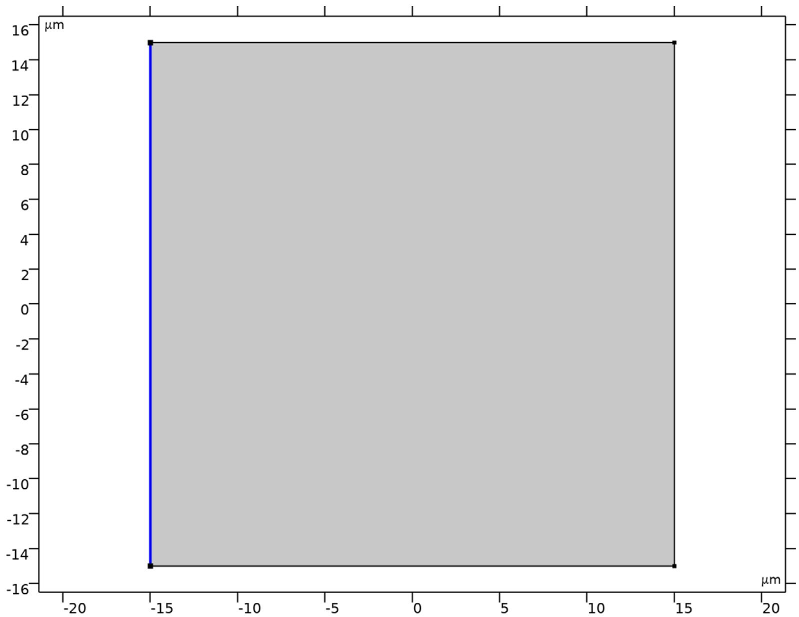
3 From the **Electric field components solved for** list, choose **Out-of-plane vector**.

Reference Scattering Boundary Condition

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

2 In the **Settings** window for **Scattering Boundary Condition**, type `Reference Scattering Boundary Condition` in the **Label** text field.

3 Select Boundary 1 only.



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
`exp(-(y/w_r)^6)`	z

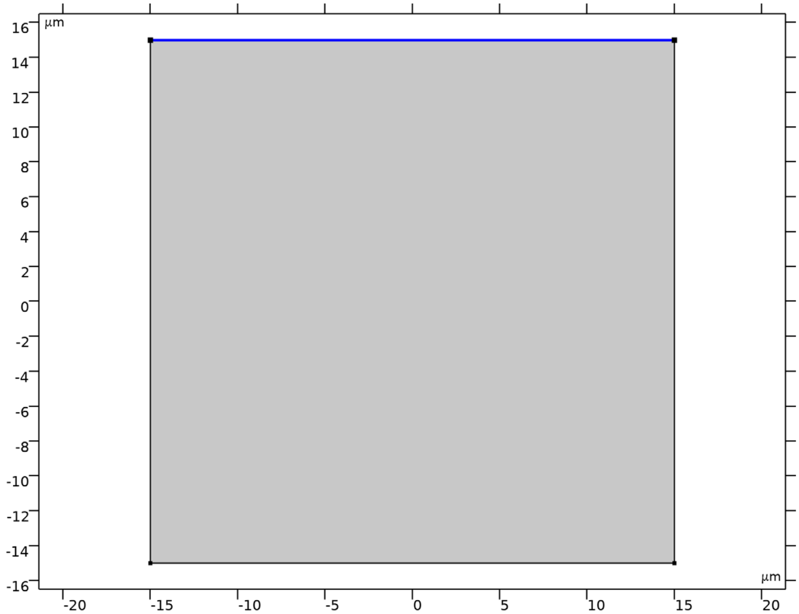
This defines the input electric field for the reference beam.

Object Scattering Boundary Condition

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

2 In the **Settings** window for **Scattering Boundary Condition**, type `Object Scattering Boundary Condition` in the **Label** text field.

3 Select Boundary 3 only.



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

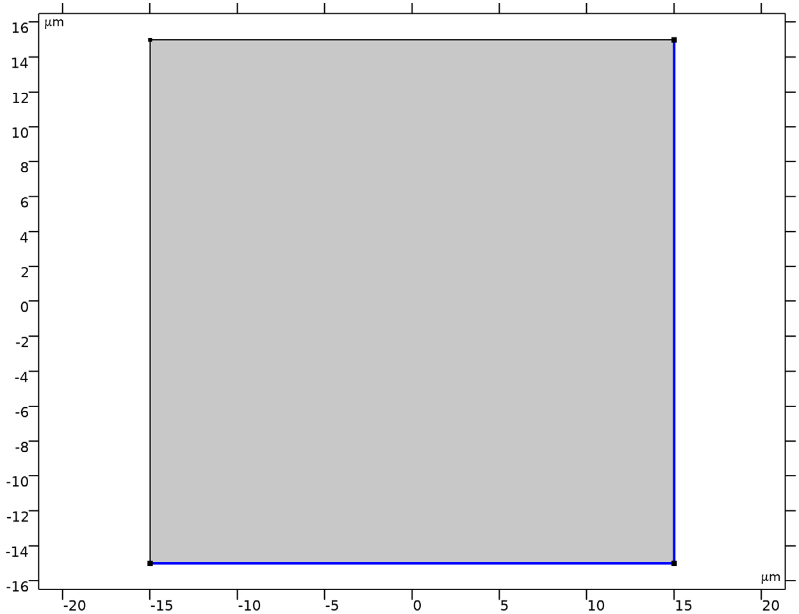
`0`	x
`0`	y
`exp(-x^6/w_o^6)`	z

Recording Scattering Boundary Condition

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

2 In the **Settings** window for **Scattering Boundary Condition**, type `Recording Scattering Boundary Condition` in the **Label** text field.

3 Select Boundaries 2 and 4 only.



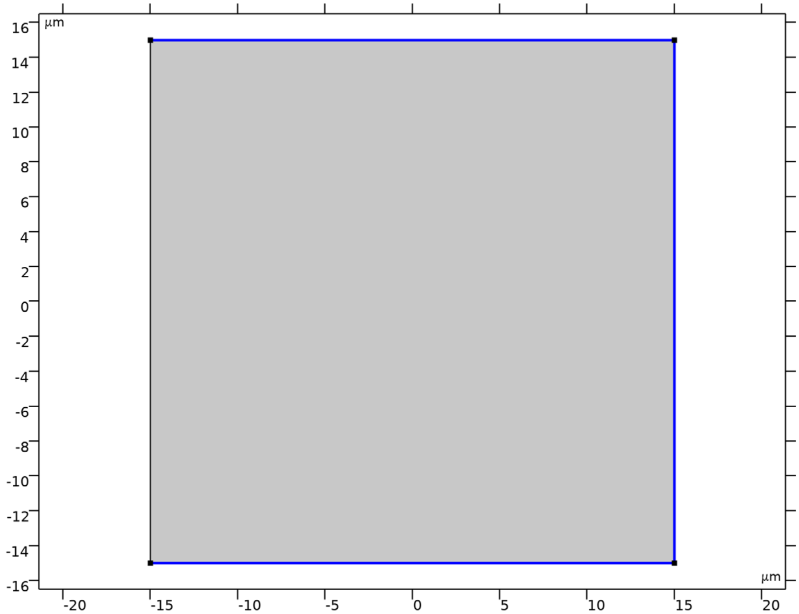
4 Right-click **Recording Scattering Boundary Condition** and choose **Duplicate**.

Retrieval Scattering Boundary Condition

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)** click **Recording Scattering Boundary Condition 1**.

2 In the **Settings** window for **Scattering Boundary Condition**, type `Retrieval Scattering Boundary Condition` in the **Label** text field.

3 Select Boundaries 2–4 only.



MESH 1

Free Triangular 1

Set the maximum mesh element size to be one tenth of the material wavelength.

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 `wl0/n1/10`.

STUDY 1

Now, define the two study steps.

Recording

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

2 In the **Settings** window for **Wavelength Domain**, type `Recording` in the **Label** text field.

3 Locate the **Study Settings** section. In the **Wavelengths** text field, type `wl0`.
4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.
5 In the tree, select **Component 1 (comp1)>Definitions>Refractive Index During Retrieval**.
6 Right-click and choose **Disable**.
7 In the tree, select **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)>Retrieval Scattering Boundary Condition**.
8 Right-click and choose **Disable**.

Step 1: Recording

Right-click **Step 1: Recording** and choose **Duplicate**.

Retrieval

1 In the **Model Builder** window, under **Study 1** click **Step 2: Recording 1**.
2 In the **Settings** window for **Wavelength Domain**, type `Retrieval` in the **Label** text field.
3 Locate the **Physics and Variables Selection** section. In the tree, select **Component 1 (comp1)>Definitions>Refractive Index During Recording**.
4 Right-click and choose **Disable**.
5 In the tree, select **Component 1 (comp1)>Definitions>Refractive Index During Retrieval**.
6 Right-click and choose **Enable**.
7 In the tree, select **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)>Recording Scattering Boundary Condition**.
8 Right-click and choose **Disable**.
9 In the tree, select **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)>Retrieval Scattering Boundary Condition**.
10 Right-click and choose **Enable**.

Solution 1 (sol1)

Before clicking **Compute**, add a **Solution Store**, after the node **Stationary Solver 1**, to store the solution from the first study step.

1 In the **Study** toolbar, click **Show Default Solver**.

Move the node **Solution Store 1** to be located between **Stationary Solver 1** and **Compile Equations: Retrieval**.

2 Right-click **Solution 1 (sol1)** and choose **Other>Solution Store**.
3 In the **Study** toolbar, click **Compute**.

RESULTS

Recording

Modify the default plot to show the interference between the reference beam and the object beam, by displaying the electric field and the square of the norm of the electric field.

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

2 From the **Dataset** list, choose **Study 1/Solution Store 1 (sol2)**. This selects the dataset for the first study step.>

3 In the **Label** text field, type `Recording`.

Surface 1

1 In the **Model Builder** window, expand the **Recording** 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. Clear the **Color legend** check box.

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

Surface 2

1 In the **Model Builder** window, click **Surface 2**.

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

3 In the **Expression** text field, type `ewfd.normE^2`.

Translation 1

1 Right-click **Surface 2** and choose **Translation**.

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

3 In the **x** text field, type `34`.

Recording

1 In the **Model Builder** window, under **Results** click **Recording**.

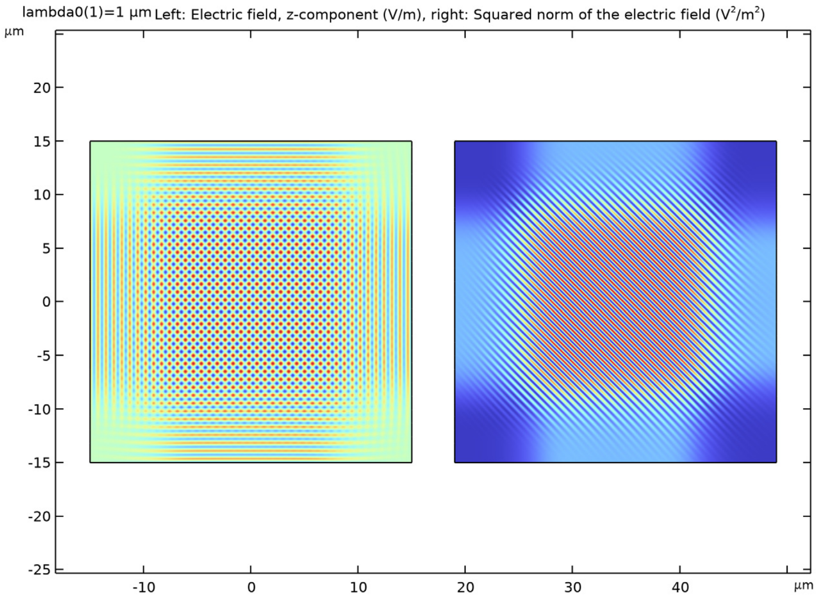
2 In the **Settings** window for **2D Plot Group**, click to expand the **Title** section.

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

4 In the **Title** text area, type `Left: Electric field, z-component (V/m), right: Squared norm of the electric field (V<sup>2</sup>/m<sup>2</sup>)`.

5 In the **Recording** toolbar, click **Plot**.

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



Now, duplicate this plot group to create a plot of the modulated refractive index.

7 Right-click **Results>Recording** and choose **Duplicate**.

Surface 2

1 In the **Model Builder** window, expand the **Recording 1** node.

2 Right-click **Surface 2** and choose **Delete**.

Modulated Refractive Index

1 In the **Model Builder** window, under **Results** click **Recording 1**.

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

3 Locate the **Title** section. In the **Title** text area, type `Modulated refractive index`.

Surface 1

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

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Definitions>Variables>n_mod - Modulated refractive index**.

3 Locate the **Coloring and Style** section. Select the **Color legend** check box.

Modulated Refractive Index

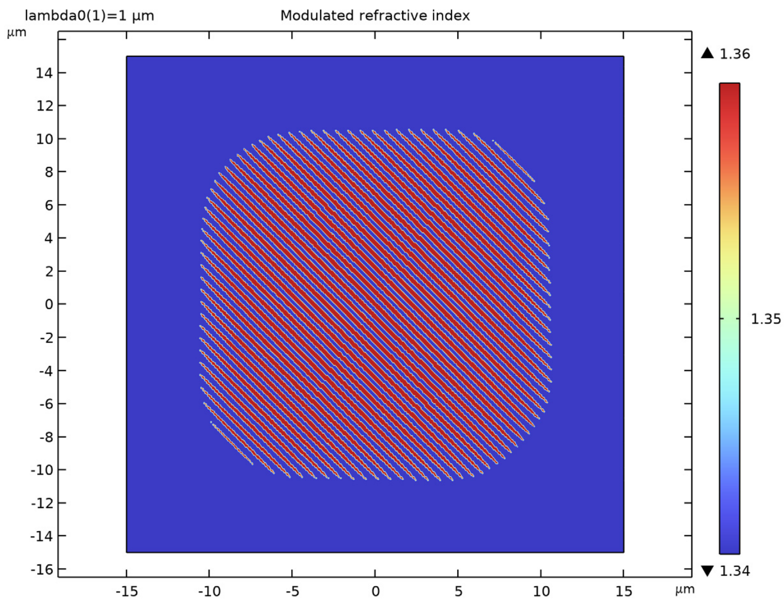
1 In the **Model Builder** window, click **Modulated Refractive Index**.

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

3 Select the **Show maximum and minimum values** check box.

4 In the **Modulated Refractive Index** toolbar, click **Plot**.

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



Cut Line 2D 1

1 In the **Results** toolbar, click **Cut Line 2D**.

2 In the **Settings** window for **Cut Line 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution Store 1 (sol2)**.

4 Locate the **Line Data** section. In row **Point 1**, set **X** to `-L/2`.

5 In row **Point 1**, set **Y** to `-H/2`.

6 In row **Point 2**, set **X** to `L/2`.

7 In row **Point 2**, set **Y** to `H/2`.

Squared Norm of the Electric Field

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

2 In the **Settings** window for **1D Plot Group**, type `Squared Norm of the Electric Field` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 2D 1**.

Line Graph 1

1 Right-click **Squared Norm of the Electric Field** and choose **Line Graph**.

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

3 In the **Expression** text field, type `ewfd.normE^2`.

4 Click to expand the **Legends** section. Select the **Show legends** check box.

5 From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
ewfd.normE²

7 Right-click **Line Graph 1** and choose **Duplicate**.

Line Graph 2

1 In the **Model Builder** window, click **Line Graph 2**.

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

3 In the **Expression** text field, type `threshold*maxop1(ewfd.normE^2)`.

4 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Red**.

5 From the **Width** list, choose **4**.

6 Locate the **Legends** section. In the table, enter the following settings:

Legends
threshold*maxop1(ewfd.normE²)

Squared Norm of the Electric Field

1 In the **Model Builder** window, click **Squared Norm of the Electric Field**.

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

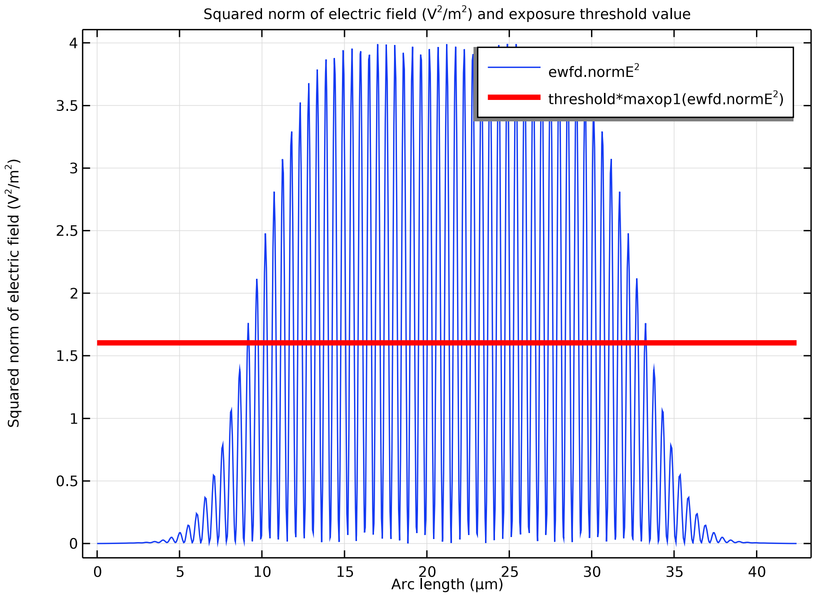
3 From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Squared norm of electric field (V<sup>2</sup>/m<sup>2</sup>) and exposure threshold value`.

5 Locate the **Plot Settings** section.

6 Select the **y-axis label** check box. In the associated text field, type `Squared norm of electric field (V<sup>2</sup>/m<sup>2</sup>)`.

7 In the **Squared Norm of the Electric Field** toolbar, click **Plot**.



Modulated Refractive Index Line Plot

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

2 In the **Settings** window for **1D Plot Group**, type `Modulated Refractive Index Line Plot` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 2D 1**.

Line Graph 1

1 Right-click **Modulated Refractive Index Line Plot** and choose **Line Graph**.

2 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)>Definitions>Variables>n_mod - Modulated refractive index**.

Modulated Refractive Index Line Plot

1 In the **Model Builder** window, click **Modulated Refractive Index Line Plot**.

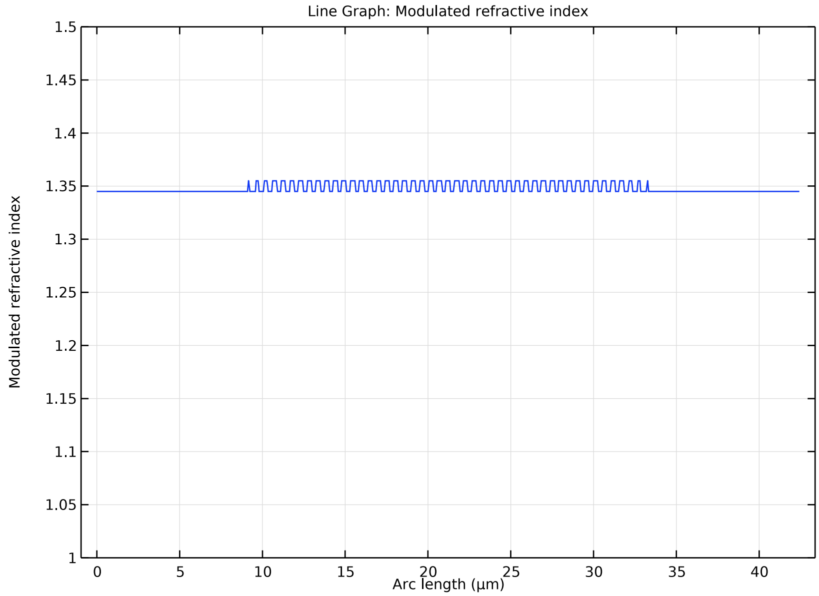
2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.

3 Select the **Manual axis limits** check box.

4 In the **y minimum** text field, type `1`.

5 In the **y maximum** text field, type `1.5`.

6 In the **Modulated Refractive Index Line Plot** toolbar, click **Plot**.



Recording

In the **Model Builder** window, right-click **Recording** and choose **Duplicate**.

Retrieval (Reference Only)

1 In the **Model Builder** window, under **Results** click **Recording 1**.

2 In the **Settings** window for **2D Plot Group**, type `Retrieval (Reference Only)` in the **Label** text field.

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

4 Locate the **Title** section. In the **Title** text area, type `Left: Electric field, z-component (V/m), right: Norm of the electric field (V/m)`.

Surface 2

1 In the **Model Builder** window, expand the **Retrieval (Reference Only)** node, then click **Surface 2**.

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

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

4 In the **Retrieval (Reference Only)** toolbar, click **Plot**.

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