Created in COMSOL Multiphysics 5.6

Slot Waveguide

Introduction

Research in the field of photonic integrated circuits (PICs) is taking a boost, especially because of its compatibility with the existing CMOS fabrication techniques using materials such as silicon (Si) and silicon dioxide (SiO_2). Doing extensive numerical simulations on the photonic component design before fabricating the final prototype essentially saves resources.

Optical waveguides are extensively used in PICs. They have the responsibility to transfer optical energy and signals from one optical component to another. Exhaustive research has been performed with a particular type of configuration of the optical waveguide where the high refractive index medium (core) is wrapped around by a low refractive index medium (cladding). The physics behind transferring the energy in such core/cladding configuration is simply based on total internal reflection (TIR). For more information about traditional optical waveguides, see for example Ref. 1.

However counterintuitive, research is also carried out where the optical energy is made to confine within the low refractive index slot placed bordering two high refractive index slabs as shown in the Figure 1. This is the slot waveguide configuration.

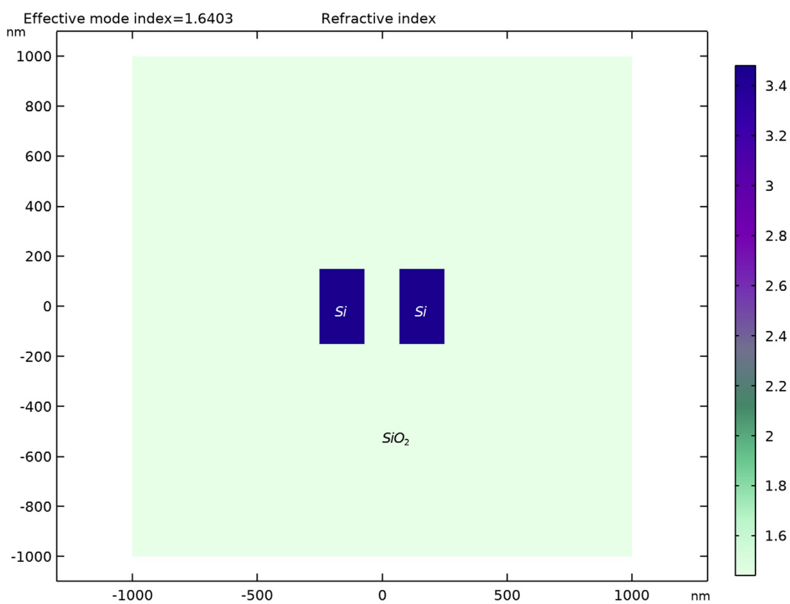


Figure 1: The slot waveguide geometry, also indicating the materials and their respective refractive indices.

Maxwell's equations state that the normal component of the electric displacement field (the D field) must be continuous across interfaces between materials with different refractive indices. Thus, the normal component of the electric field (E field) must be higher in the material with the low refractive index. This can be used to enhance and confine the guided mode into a narrow domain with low refractive index — the slot domain.

The dimension of this low refractive index domain is in orders of tens of nanometers which keeps the optical energy tightly confined to a narrow area giving a high optical energy density in the waveguide.

For more information about this slot waveguide structure, see Ref. 2.

Model Definition

Mode analysis is performed on the cross section of the optical waveguide rather than modeling the complete 3D geometry.

The wave is propagating out of the plane in z direction, as shown below

$$E(x, y, z) = E(x, y)e^{j(\omega t - \beta z)}, \tag{1}$$

where ω is the angular frequency and β is the propagation constant.

The eigenvalue equation for the electric field is obtained from the Helmholtz equation

$$\nabla\times(\nabla\times E) - k_0^2 n^2 = 0 \tag{2}$$

The above equation is solved for the eigenvalue $\lambda = -j\beta$.

As shown in Figure 1, the silicon dioxide slot has a refractive index of 1.44, while the neighboring silicon slabs has a refractive index of 3.48.

After the mode analysis was performed, to optimize the width of the nano-slot to provide the maximum optical power through the waveguide, a parametric sweep of the width from 30 nm to 140 nm was performed.

To evaluate the normalized optical power and optical intensity through the waveguide, two integration operators were defined; first to perform an integration over the slot area and second for the complete waveguide area. A maximum operator was used to evaluate the normalized transverse electric field (E_x) through the center of the waveguide.

Results and Discussion

The mode analysis evaluates the fundamental mode for a slot width of 50 nm at an operating wavelength of 1.55 µm. The surface plot showcases the in-plane transverse electric field (E_x) confined in the narrow slot as shown in the Figure 2.

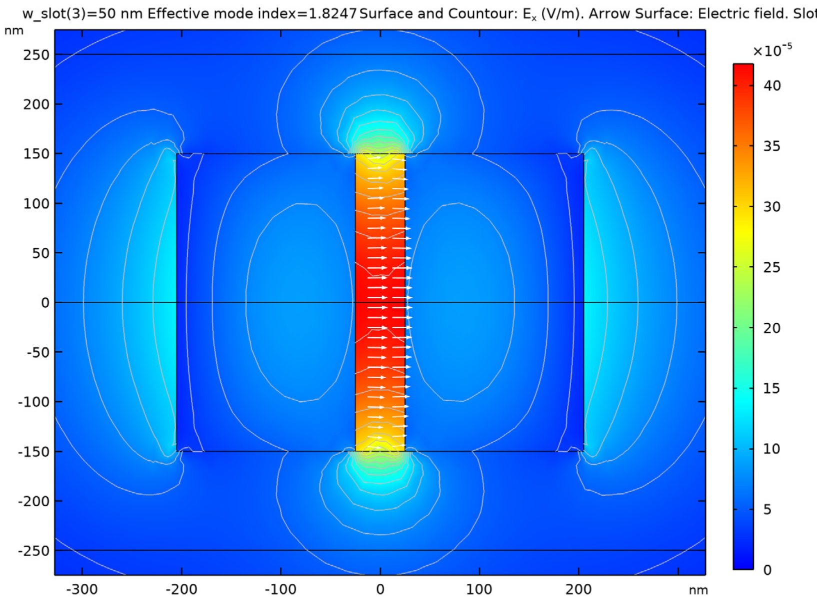


Figure 2: Schematic of the 50 nm width slot waveguide configuration with the transverse electric field (E_x) surface plot. The effective mode index is 1.8247.

The ratio of E_x over the absolute maximum of E_x was used to evaluate the normalized x component of the transverse electric field through the center of the waveguide, as shown in Figure 3. A large discontinuity in the electric field can be observed specifically at ±25 nm.

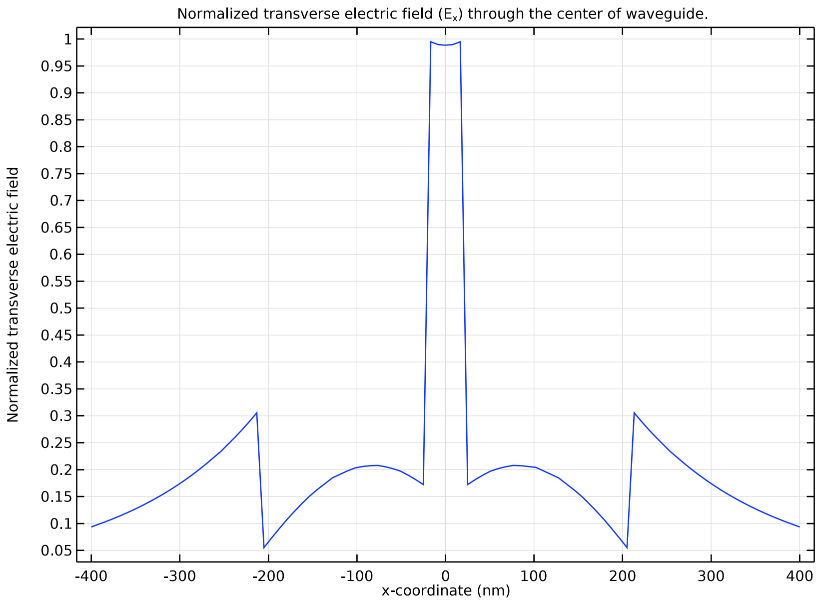


Figure 3: Normalized transverse electric field ($\boldsymbol{E_x}$) through the center of the waveguide.

To visualize this discontinuity more comprehensively, a surface plot along with the height expression was plotted as shown in Figure 4.

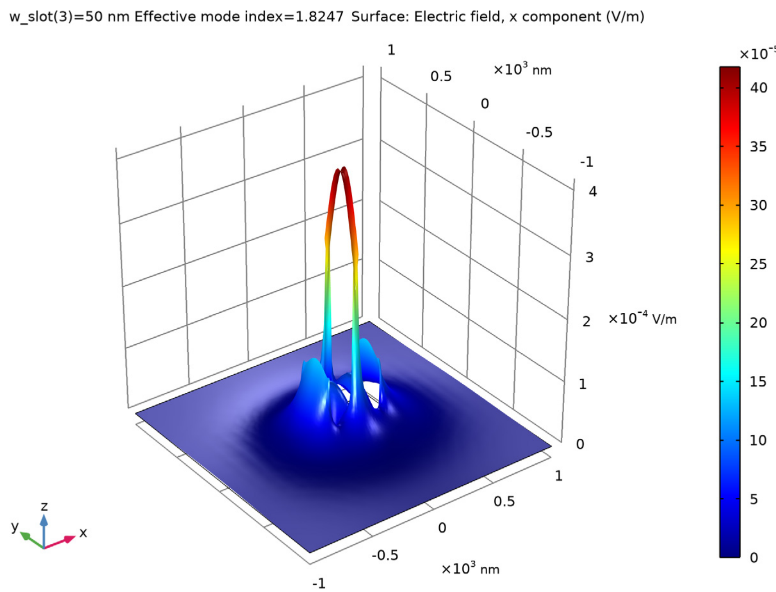


Figure 4: Surface plot along with its height expression to visualize a 3D representation of the transverse electric field $\mathbf{E}_x$.

Finally, the normalized power and intensity through the waveguide with respect to the different slot width is highlighted in Figure 5. The normalized quantities were derived as the ratio of integrated optical power and optical intensity in the slot over the integrated optical power and optical intensity through the complete waveguide. It could be emphasized that the normalized optical power peaks for the slot width between 50 nm and 120 nm.

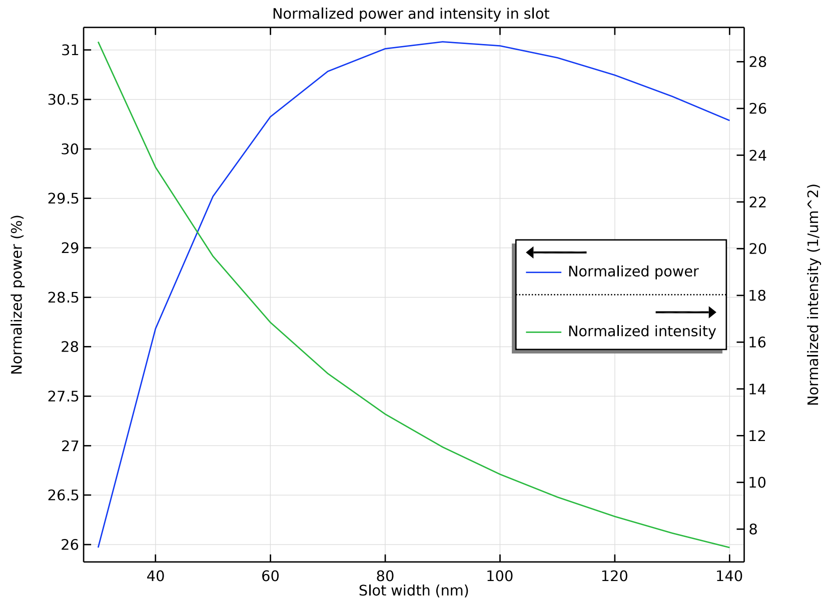


Figure 5: Normalized optical power and optical intensity through the slot with respect to the slot width for an operating wavelength of 1.55 µm.

References

1. B.E.A. Saleh and M.C. Teich, *Fundamentals of Photonics*, John Wiley & Sons, Inc., chap. 7, 1991.

2. V. Almeida, Q. Xu, C. Barrios, and M. Lipson, "Guiding and confining light in void nanostructure", *Optics Letters*, vol. 29, pp. 1209–1211, 2004.

Application Library path: `Wave_Optics_Module/Waveguides_and_Couplers/slot_waveguide`

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>Mode Analysis**.
6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

Start by adding some parameters that will simplify the setup of the geometry, the materials, and the study.

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 In the table, enter the following settings:

Name	Expression	Value	Description
w_slab	180[nm]	1.8E-7 m	Width of slab
w_slot	50[nm]	5E-8 m	Width of slot
h_slot	300[nm]	3E-7 m	Height of slot
lda0	1.55[um]	1.55E-6 m	Operating wavelength
f0	c_const/lda0	1.9341E14 1/s	Operating frequency
n_slab	3.48	3.48	Refractive index of slab
n_slot	1.44	1.44	Refractive index of slot
n_clad	1.44	1.44	Refractive index of cladding
a	2[um]	2E-6 m	Exterior domain side length
b	800[nm]	8E-7 m	Interior domain width
c	500[nm]	5E-7 m	Interior domain height

GEOMETRY 1

The geometry consists of a number of rectangles defining the slot, the slabs, and the cladding domain.

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 **nm**.

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 `w_slot`.
4 In the **Height** text field, type `h_slot`.
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 `w_slab`.
4 In the **Height** text field, type `h_slot`.
5 Locate the **Position** section. In the **x** text field, type `w_slot/2`.
6 In the **y** text field, type `-h_slot/2`.
7 Click **Build Selected**.

Move 1 (mov1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Move**.
2 Select the object **r2** only.
3 In the **Settings** window for **Move**, locate the **Input** section.
4 Select the **Keep input objects** check box.
5 Locate the **Displacement** section. In the **x** text field, type `-w_slot-w_slab`.
6 Click **Build Selected**.

Rectangle 3 (r3)

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 `a`.

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

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

6 Click **Build Selected**.

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

Rectangle 4 (r4)

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 `b`.

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

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

6 Click **Build Selected**.

Line Segment 1 (ls1)

Add a line segment to define a line through the center of the waveguide.

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

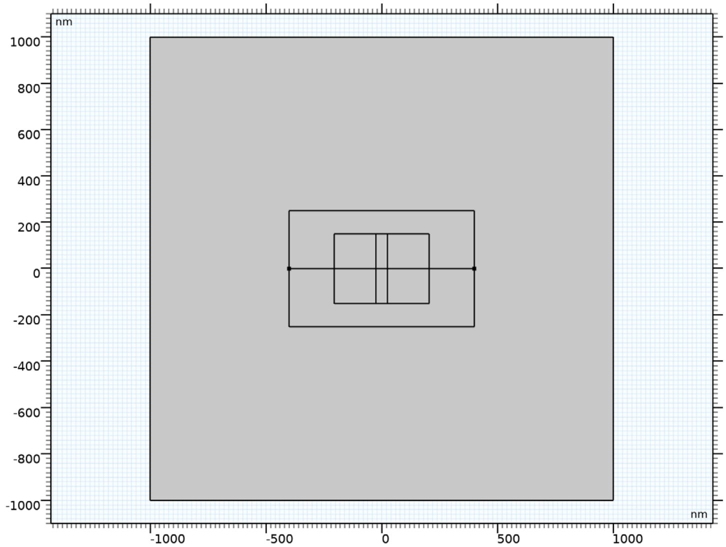
3 From the **Specify** list, choose **Coordinates**.

4 In the **x** text field, type `-b/2`.

5 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

6 In the **x** text field, type `b/2`.

7 Click **Build All Objects**.



DEFINITIONS

Now, add an operator taking the maximum value of a variable defined on the centerline through the waveguide.

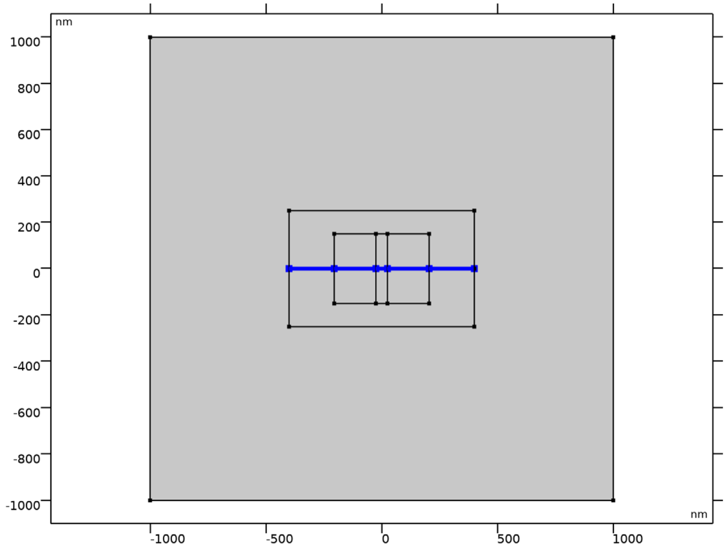
Maximum 1 (Center)

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

2 In the **Settings** window for **Maximum**, type `Maximum 1 (Center)` in the **Label** text field.

3 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundaries 7, 12, 17, 22, and 26 only.



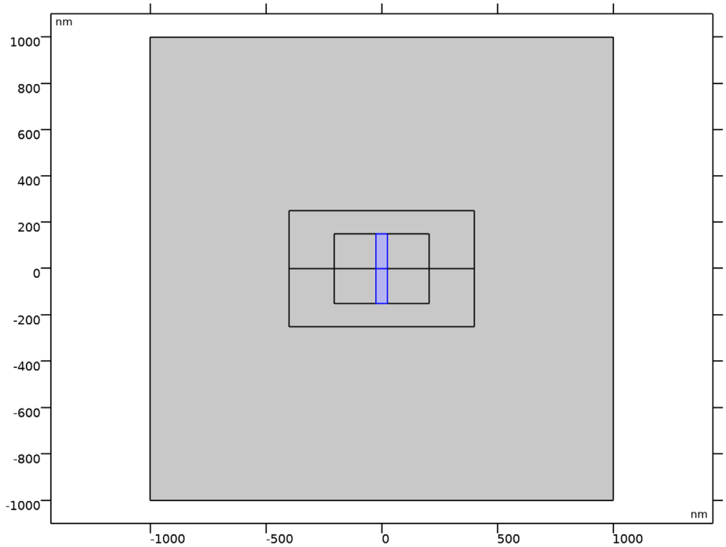
Integration 1 (Slot)

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

This integration operator should be defined for the slot domain.

2 In the **Settings** window for **Integration**, type `Integration 1 (Slot)` in the **Label** text field.

3 Select Domains 6 and 7 only.



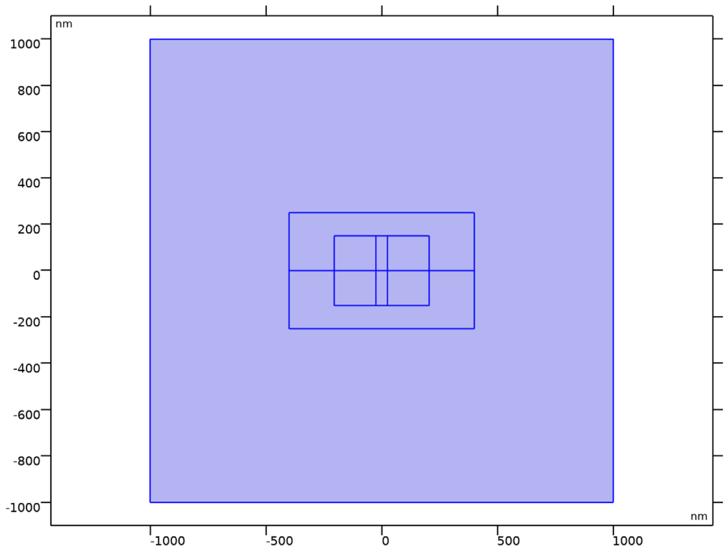
Integration 2 (Complete Waveguide)

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

This integration operator is defined for the whole waveguide structure.

2 Click in the **Graphics** window and then press Ctrl+A to select all domains.

3 In the **Settings** window for **Integration**, type `Integration 2 (Complete Waveguide)` in the **Label** text field.



MATERIALS

Now, define the materials in the waveguide structure.

Slot

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

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

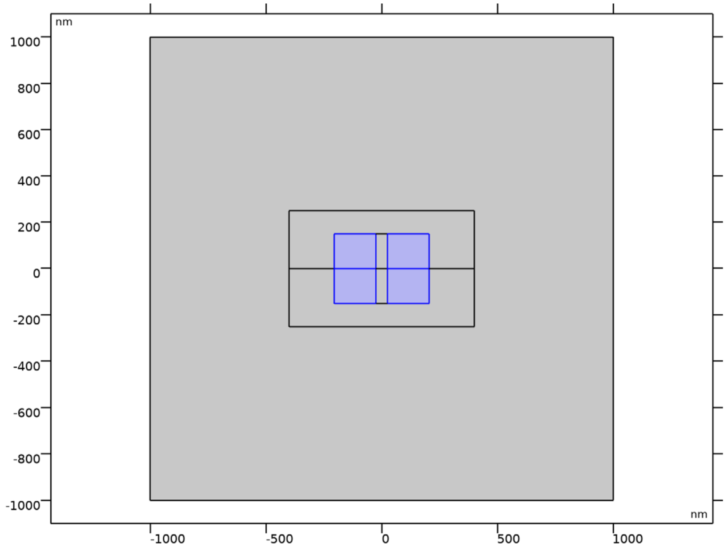
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_slot`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

Slab

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

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

3 Select Domains 4, 5, 8, and 9 only.



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

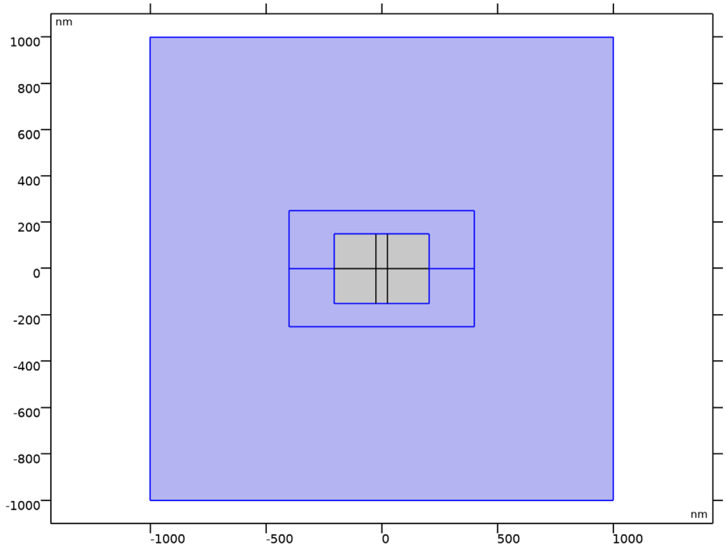
Property	**Variable**	**Value**	**Unit**	**Property group**
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_slab`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

Cladding

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

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

3 Select Domains 1–3 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_clad`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

MESH 1

Define a manual mesh sequence. The physics-controlled mesh sequence will be the starting point.

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

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

3 From the **Sequence type** list, choose **User-controlled mesh**.

Size

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

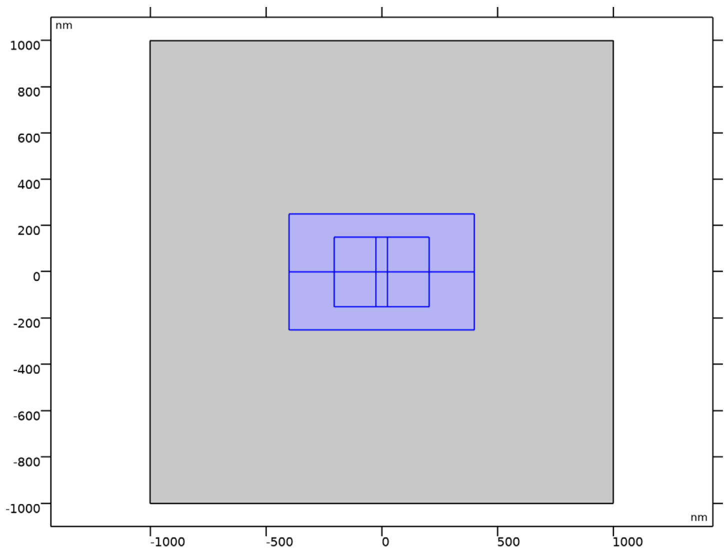
2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 Click the **Predefined** button.

Size 1

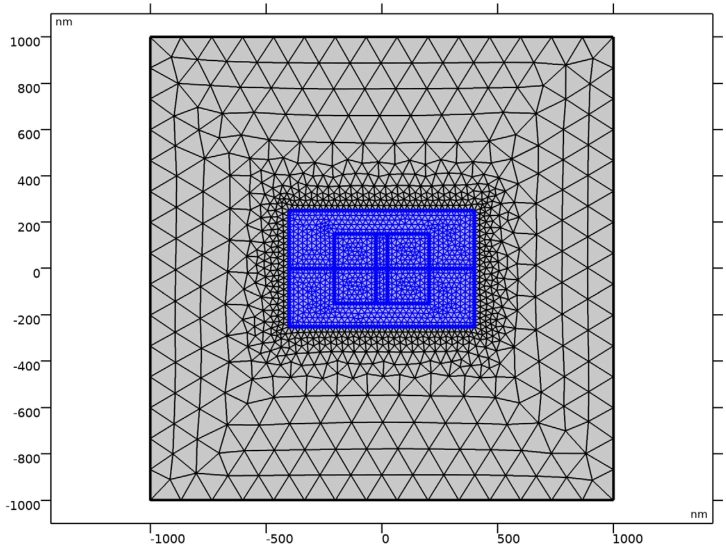
This size node will set the maximum mesh element size for the center part of the waveguide structure to be one twentieth of its height.

1. In the **Model Builder** window, click **Size 1**.
2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domains 2–9 only.



5. Locate the **Element Size** section. Click the **Custom** button.
6. Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.
7. In the associated text field, type `c/20`.

8 Click **Build All**.



STUDY 1

Step 1: Mode Analysis

1 In the **Model Builder** window, under **Study 1** click **Step 1: Mode Analysis**.

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

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

4 Select the **Desired number of modes** check box.

5 In the associated text field, type `2`.

6 Select the **Search for modes around** check box.

7 In the associated text field, type `n_slab`.

Add a parameteric sweep over the slot width.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
w_slot (Width of slot)		m

5 Click to select row number 1 in the table.

6 Click **Range**.

7 In the **Range** dialog box, type `30[nm]` in the **Start** text field.

8 In the **Step** text field, type `10[nm]`.

9 In the **Stop** text field, type `140[nm]`.

10 Click **Replace**.

11 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

12 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
w_slot (Width of slot)	`range(30[nm],10[nm], 140[nm])`	nm

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

RESULTS

Electric Field (ewfd)

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

2 From the **Parameter value (w_slot (nm))** list, choose **50**.

Surface 1

1 In the **Model Builder** window, expand the **Electric Field (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.Ex`.

Contour 1

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

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

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

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

6 Clear the **Color legend** check box.

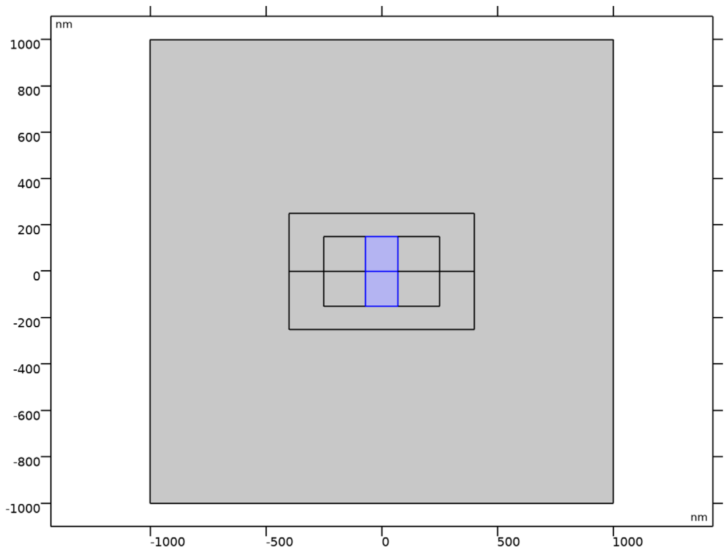
Arrow Surface 1

Right-click **Electric Field (ewfd)** and choose **Arrow Surface**.

Selection 1

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

2 Select Domains 6 and 7 only.



Arrow Surface 1

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

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

3 Locate the **Arrow Positioning** section. Find the **X grid points** subsection. In the **Points** text field, type 2.

4 Find the **Y grid points** subsection. In the **Points** text field, type 30.

5 Locate the **Coloring and Style** section. Select the **Scale factor** check box.

6 In the associated text field, type 50000.

7 From the **Color** list, choose **White**.

Electric Field (ewfd)

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

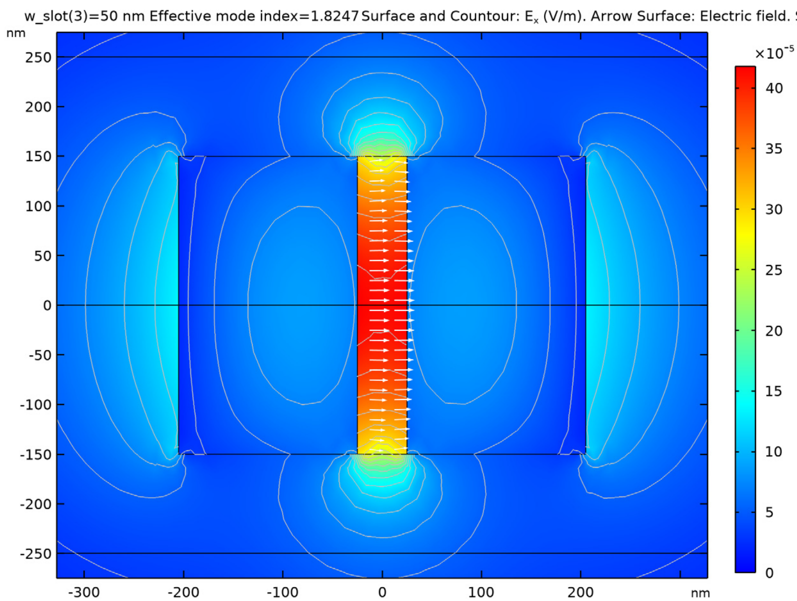
2 In the **Settings** window for **2D Plot Group**, click to expand the **Title** section.

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

4 In the **Title** text area, type Surface and Countour: E_x (V/m). Arrow Surface: Electric field. Slot width: 50 nm.

5 Click the **Zoom In** button in the **Graphics** toolbar twice to see the electric field enhancement in the slot region and to verify that the main electric field component indeed is the *x* component.

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



Add a Cut Line dataset for later use in a line graph.

Cut Line 2D 1

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Datasets** and choose **Cut Line 2D**.

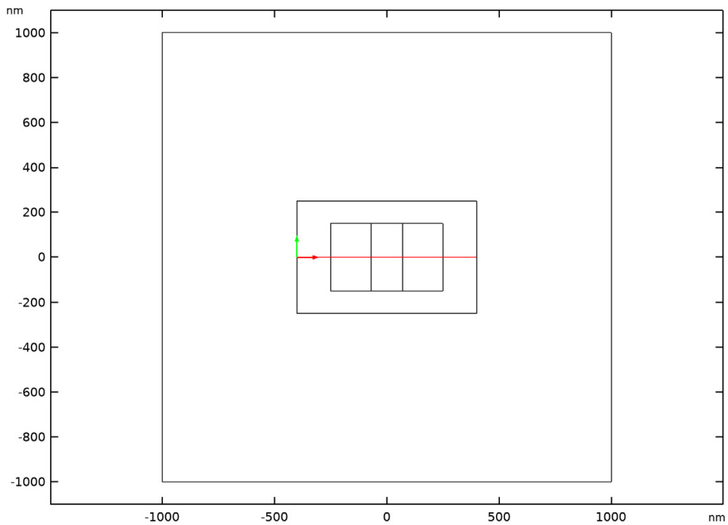
3 In the **Settings** window for **Cut Line 2D**, locate the **Data** section.

4 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

5 Locate the **Line Data** section. In row **Point 1**, set **X** to -b/2.

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

7 Click **Plot**.



Normalized Transverse Electric Field

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Cut Line 2D 1**. Using the Cut Line dataset instead of a line selection will make the line appear as continuous also at points where the data actually is discontinuous.

4 From the **Parameter selection (w_slot)** list, choose **From list**.

5 In the **Parameter values (w_slot (nm))** list, select **50**.

6 From the **Effective mode index selection** list, choose **First**.

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

8 In the **Title** text area, type Normalized transverse electric field (E_x) through the center of waveguide..

9 Locate the **Plot Settings** section. Select the **y-axis label** check box.

10 In the associated text field, type `Normalized transverse electric field`.

Line Graph 1

1 Right-click **Normalized Transverse Electric Field** and choose **Line Graph**.

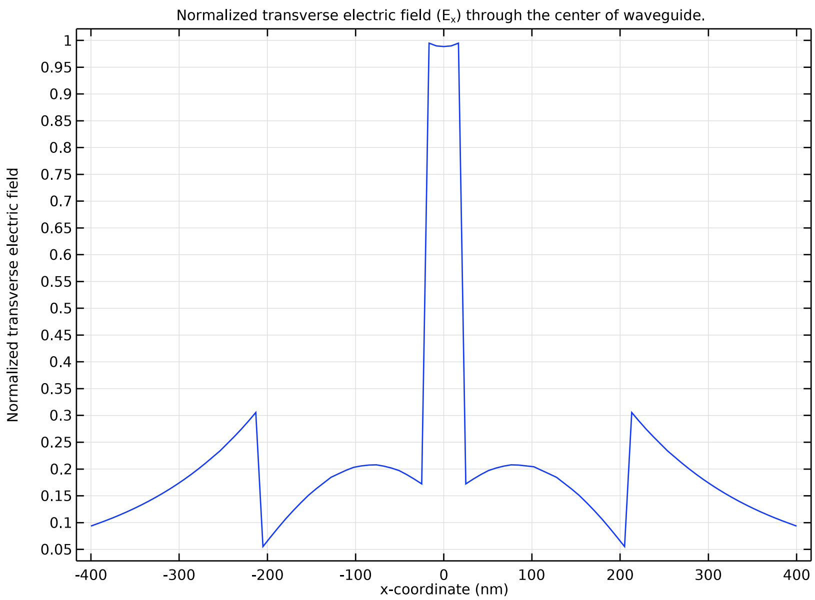
2 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `ewfd.Ex/maxop1(ewfd.Ex)`.

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

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

6 In the **Normalized Transverse Electric Field** toolbar, click **Plot**.



Transverse Electric Field

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 From the **Parameter value (w_slot (nm))** list, choose **50**.

Surface 1

1 Right-click **Transverse Electric Field** and choose **Surface**.

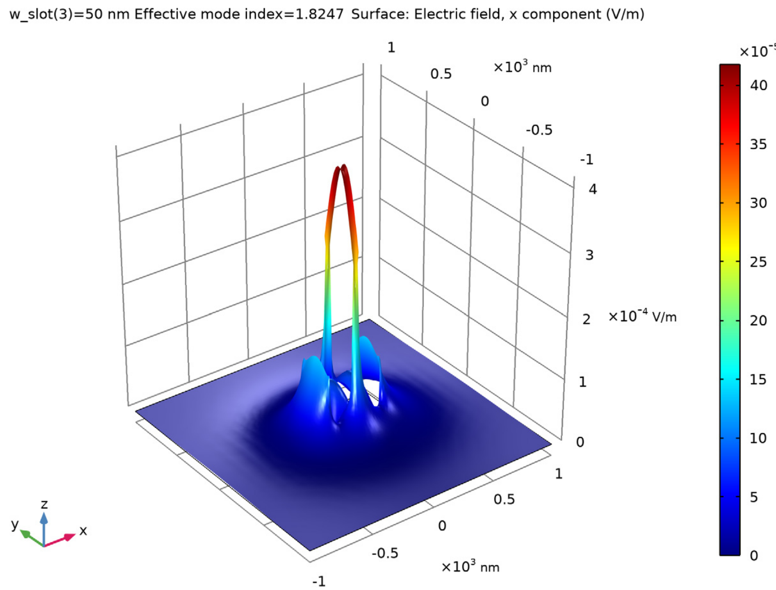
2 In the **Settings** window for **Surface**, locate the **Expression** section.

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

Height Expression 1

Add a height expression node to more clearly visualize the electric field enhancement in the slot region.

Right-click **Surface 1** and choose **Height Expression**.



Normalized Power and Intensity

Finally, add plots of the normalized power and intensity versus the slot width.

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
2 In the **Settings** window for **1D Plot Group**, type `Normalized Power and Intensity` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.
4 From the **Effective mode index selection** list, choose **First**.
5 Locate the **Title** section. From the **Title type** list, choose **Manual**.
6 In the **Title** text area, type `Normalized power and intensity in slot`.
7 Locate the **Plot Settings** section. Select the **Two y-axes** check box.
8 Select the **x-axis label** check box.
9 In the associated text field, type `Slot width (nm)`.

10 Select the **y-axis label** check box.

11 In the associated text field, type `Normalized power (%)`.

12 Select the **Secondary y-axis label** check box.

13 In the associated text field, type `Normalized intensity (1/um^2)`.

Global 1

1 Right-click **Normalized Power and Intensity** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`intop1(ewfd.Poavz)*100/intop2(ewfd.Poavz)`	1	

4 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Outer solutions**.

5 From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `w_slot`.

7 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

8 In the table, enter the following settings:

Legends
`Normalized power`

Global 2

1 Right-click **Global 1** and choose **Duplicate**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`intop1(ewfd.Poavz)/intop2(ewfd.Poavz)/(w_slot*h_slot)`	`1/um^2`	

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

Legends
`Normalized intensity`

Normalized Power and Intensity

1 In the **Model Builder** window, click **Normalized Power and Intensity**.

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

3 In the table, select the **Plot on secondary y-axis** check box for **Global 2**.

4 Locate the **Legend** section. From the **Position** list, choose **Middle right**, to make the legend panel not cover any of the line plots.

5 In the **Normalized Power and Intensity** toolbar, click **Plot**.