Created in COMSOL Multiphysics 5.6

Threshold Gain Calculations for Vertical-Cavity Surface-Emitting Lasers (VCSELs)

Introduction

In a vertical-cavity surface-emitting laser (VCSEL) the emission of light occurs in the normal direction to the layer structure. This is contrary to the emission characteristics of the more common edge-emitting laser, where the light propagation is parallel to the layers and emission occurs through cleaved facets.

The different growth and emission characteristics of VCSELs, compared to edge-emitting lasers, give advantages when it comes to testing the samples during the fabrication steps. Tens of thousands of VCSELs can also be processed in parallel on a wafer.

The structure (see Figure 1) consists of a top and a bottom distributed Bragg reflector (DBR) structure with alternating high and low refractive index layers. Each layer in those DBR stacks is a quarter of a material wavelength thick.

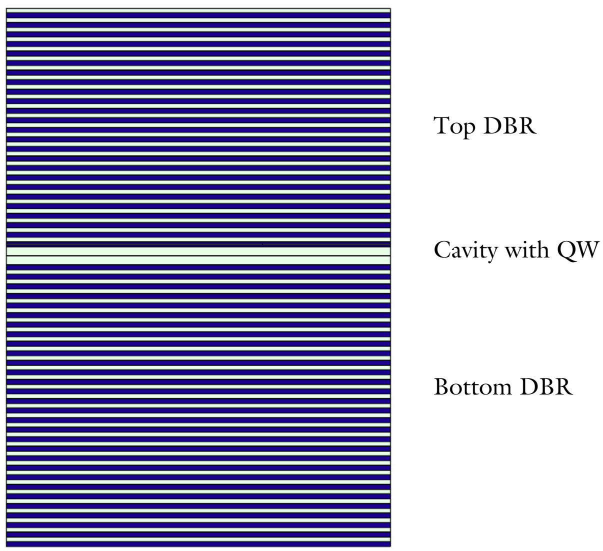


Figure 1: The structure of a vertical-cavity surface-emitting laser (VCSEL). The top and bottom distributed Bragg reflectors (DBRs) consists of alternating layers of GaAs (dark color) and AlGaAs (light color). The central cavity has one quantum well (QW) and one layer with an aluminum oxide annular ring.

The active material, providing the gain, is located in the cavity between the DBRs. It usually consists of one or more quantum well (QW) layers. A quantum well layer is a thin layer of a thickness of 100 Å or less. The band gap energy of the quantum well layers is smaller than the band gap energy of the adjacent layers. This forms a very narrow potential well, with a set of discrete energy levels. Since the energy levels depend both on the material compositions and the quantum well layer thickness, the emission wavelength can easily be changed by slightly changing the layer thicknesses and/or the material compositions.

As the quantum wells are so thin, the gain is very small. Thus, the DBRs must have a very high reflectivity — ofter larger than 99 %. Otherwise, the gain cannot balance the mirror losses.

VCSELs are used in many applications, such as for computer mice, laser printers, and in communication.

In this model, an eigenfrequency study is used to find the resonance frequency and threshold gain for an oxide-confined, GaAs-based, vertical-cavity surface-emitting laser (VCSEL). The oxide can provide both electrical and optical confinement. However, in this model only the optical properties are studied.

Model Definition

The model is setup in 2D axisymmetry for the structure in Figure 1. The modes searched for have a azimuthal dependence of $\exp(-j\varphi)$, where φ is the angle of rotation around the symmetry axis. Modes with this type of azimuthal dependence can be linearly and circularly polarized and have non-zero intensity on the symmetry axis.

The simulations are performed in two steps. A regular eigenfrequency analysis is first performed, to find good initial values for the subsequent nonlinear eigenfrequency analysis.

The resonance frequencies and threshold gain compare well to values presented in Ref. 1. This paper collects the results from different computational methods on this benchmark problem.

Results and Discussion

Figure 2 shows the mode field after the initial Eigenfrequency study. The mode is confined essentially between the top and the bottom DBRs.

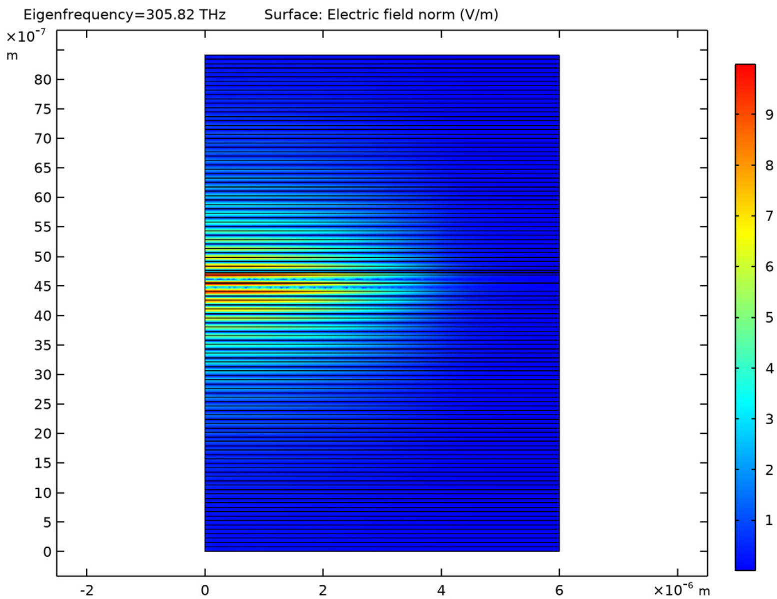


Figure 2: Surface plot of the mode field after the initial Eigenfrequency study. The plot shows the norm of the electric field, with the symmetry axis at $r = 0$.

The result after the second (nonlinear) eigenfrequency study is shown in Figure 3. Here a a height distribution feature was used to make the field distribution a bit clearer. However, the field distribution is very similar to the distribution after the first study.

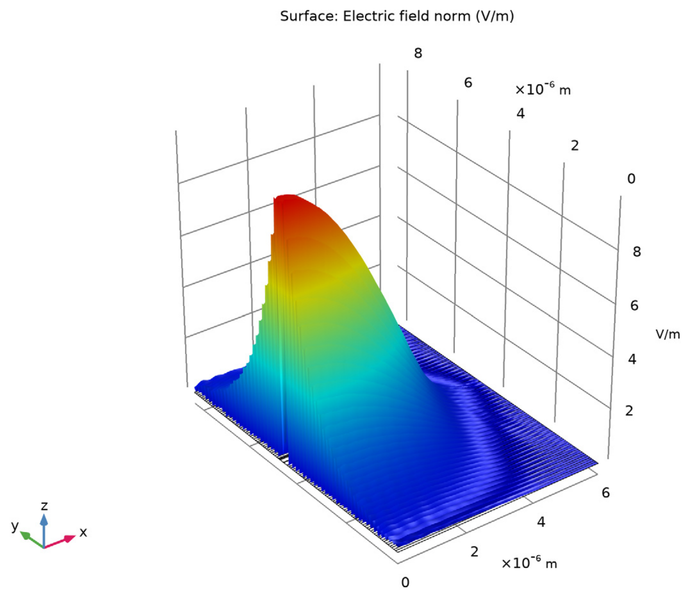


Figure 3: The mode field distribution after the second study.

The resonance wavelength and the threshold gain coefficient are summarized in Table 1 below. The results agree well with Figures. 2 and 3 in Ref. 1 for oxide position 3.

TABLE 1: RESONANCE WAVELENGTH AND THRESHOLD GAIN FOR OXIDE POSITION 3.

RESONANCE WAVELENGTH	THRESHOLD GAIN
980.3 nm	1217 cm^{-1}

Reference

1. P. Bienstman et al., "Comparison of optical VCSEL models on the simulation of oxide-confined devices," IEEE J. Quantum Electron., vol. 37, no. 12, pp. 1618-1631, 2001.

Application Library path: `Wave_Optics_Module/Verification_Examples/vertical_cavity_surface_emitting_laser`

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 Axisymmetric**.

2 In the **Select Physics** tree, select **Optics>Wave Optics>Electromagnetic Waves, Frequency Domain (ewfd)**.

3 Click **Add**.

4 Click **Add**.

5 Click **Study**.

6 In the **Select Study** tree, select **General Studies>Eigenfrequency**.

7 Click **Done**.

GEOMETRY 1

The model geometry is available as a parameterized geometry sequence in a separate MPH-file. If you want to build it from scratch, follow the instructions in Appendix: Geometry Modeling Instructions. Otherwise load it from file with the following steps.

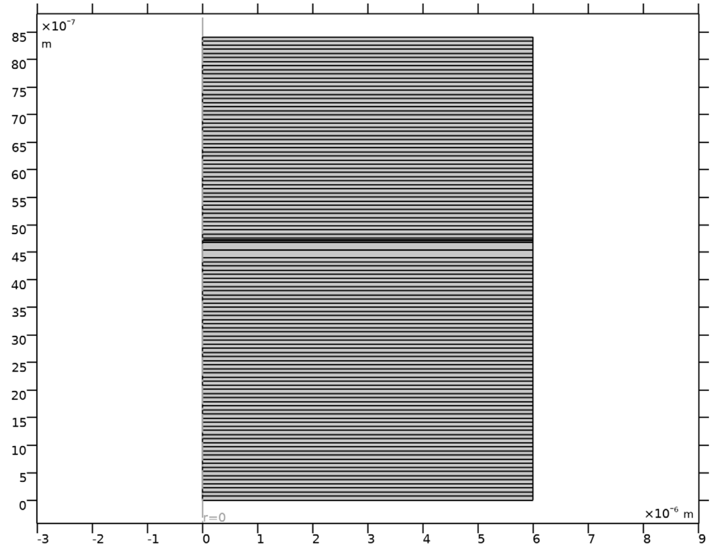
1 In the **Geometry** toolbar, click **Insert Sequence**.

2 Browse to the model's Application Libraries folder and double-click the file `vertical_cavity_surface_emitting_laser_geom_sequence.mph`.

3 In the **Insert Sequence from File** dialog box, click **OK**.

4 In the **Geometry** toolbar, click **Build All**.

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



GLOBAL DEFINITIONS

The parameters for the geometry was included in the loaded geometry sequence file.

Geometry Parameters

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, type `Geometry Parameters` in the **Label** text field.

General Parameters

Now, add some general parameters, like the intended wavelength, and some parameters defining the materials.

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

2 In the **Settings** window for **Parameters**, type `General Parameters` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model’s Application Libraries folder and double-click the file `vertical_cavity_surface_emitting_laser_general_parameters.txt`.

Material Parameters

1 In the **Home** toolbar, click **Parameters** and choose **Add>Parameters**.

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

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `vertical_cavity_surface_emitting_laser_material_parameters.txt`.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

The geometry is cylindrically symmetric. Solve for modes having an $\exp(-j\varphi)$ dependence, where φ is the rotation angle around the symmetry axis. With this rotation angle variation, the modes can be non-zero on the symmetry axis.

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 **Out-of-Plane Wave Number** section.

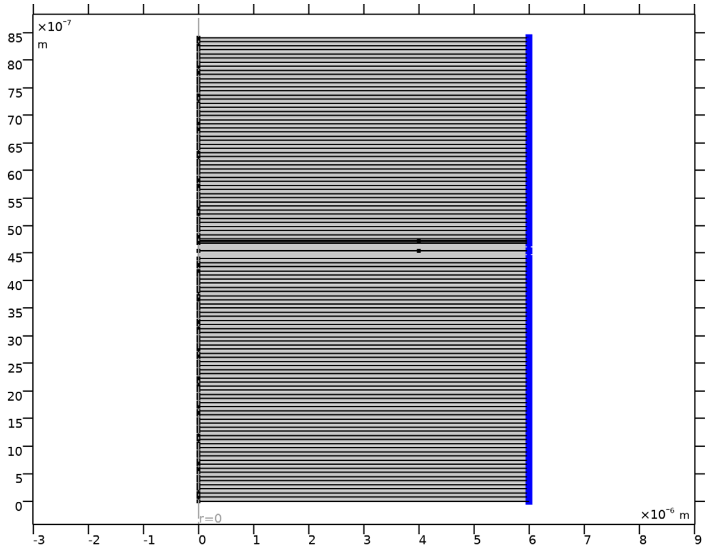
3 In the m text field, type `1`. This will give you the expected rotation angle variation, discussed above.

Scattering Boundary Condition 1

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

2 Click the **Select Box** button in the **Graphics** toolbar.

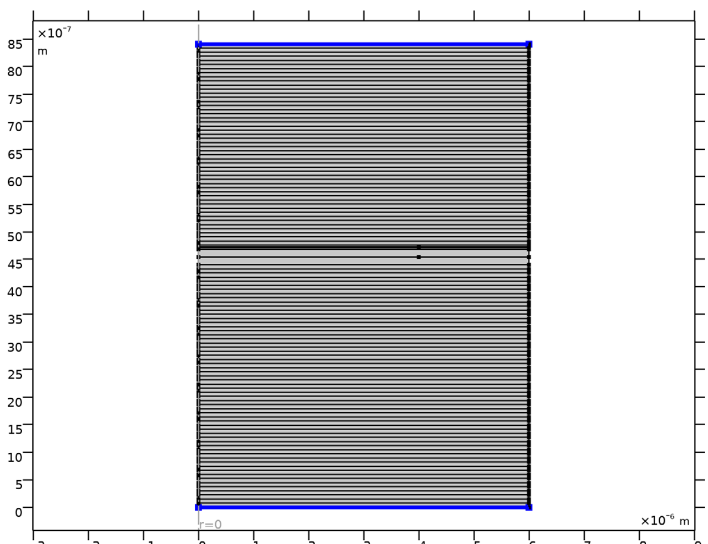
3 Select Boundaries 236–349 only. These entities constitute the outer boundary of the rotationally symmetric cylinder.



Impedance Boundary Condition 1

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

2 Select Boundaries 2 and 229 only. These are the top and bottom boundaries.

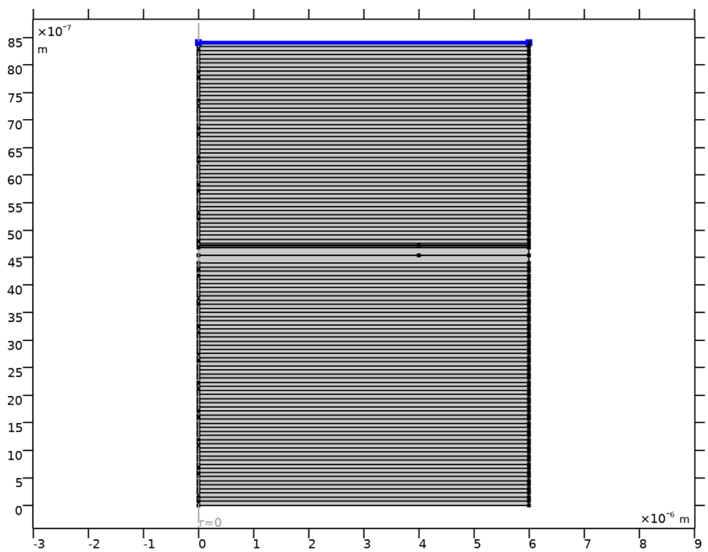


MATERIALS

Now, define all the materials for the structure. The selections that will be used was defined when the geometry was built. Please consult Appendix: Geometry Modeling Instructions for the details about defining cumulative selections when building the geometry sequence.

Air Superstrate

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 `Air Superstrate` in the **Label** text field.
3. Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Boundary**.
4. Select Boundary 229 only, which is the top boundary.



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

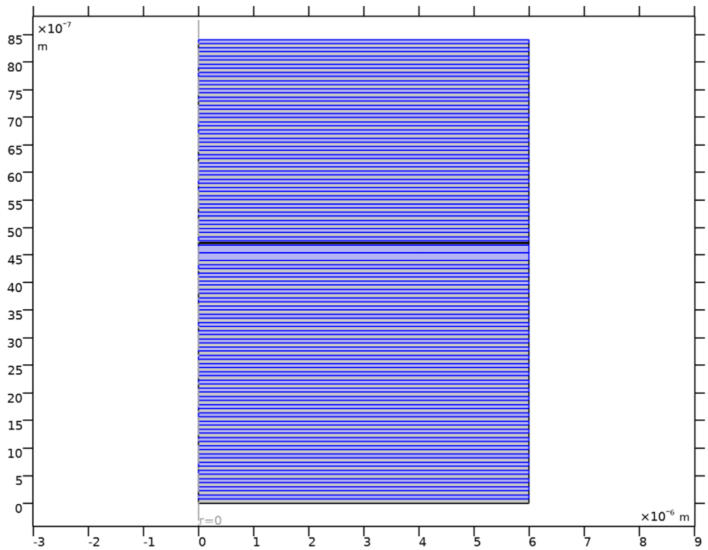
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_air`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

GaAs

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

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **GaAs Layers**.



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

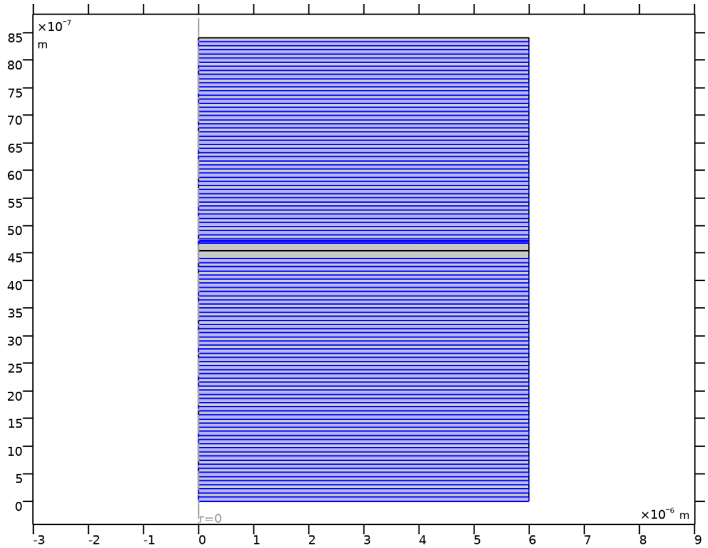
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	n_GaAs	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

AlGaAs

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

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **AlGaAs Layers**.



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

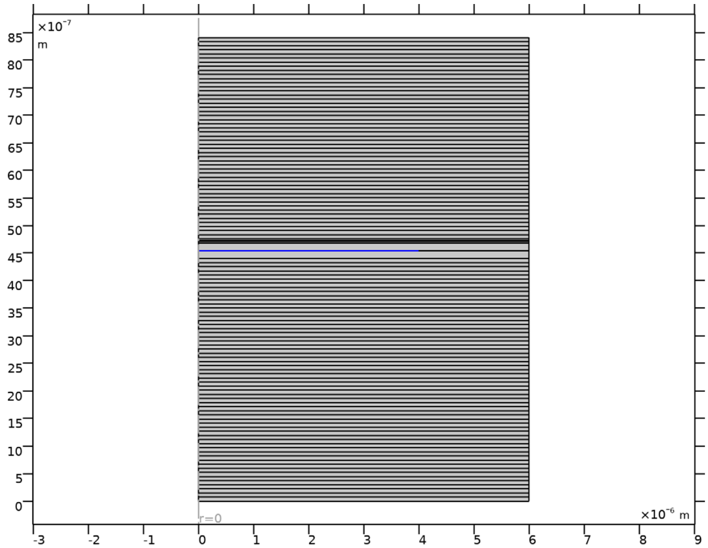
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_AlGaAs`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

QW Gain

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

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **QW Gain Domain**.



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_QW`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	`kappa_QW`	1	Refractive index

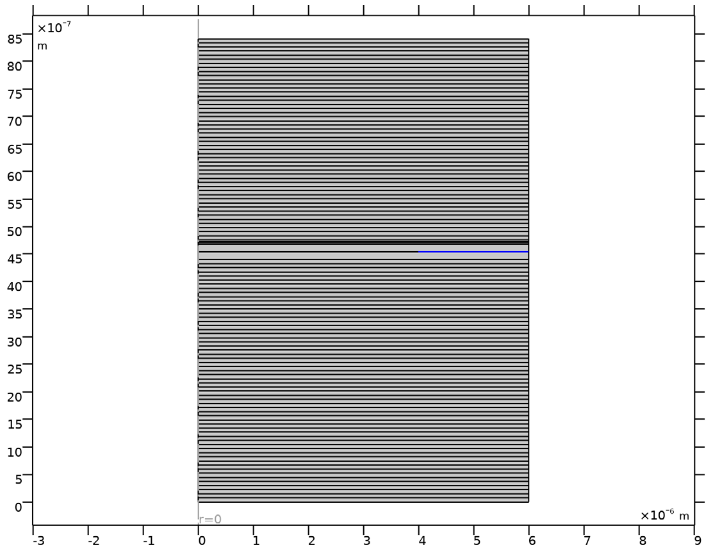
A variable named `kappa_QW` will be added after all materials have been defined.

QW Loss

1 Right-click **QW Gain** and choose **Duplicate**.

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **QW Loss Domain**.



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

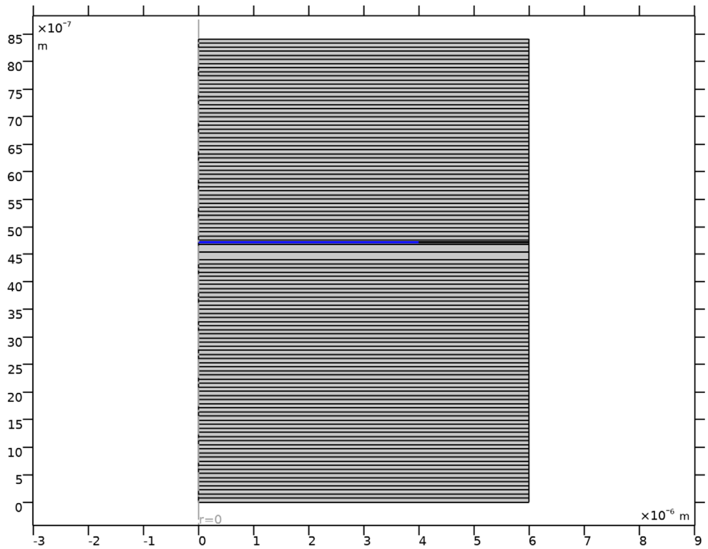
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	`n_QW`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	`kappa_QW_loss`	1	Refractive index

AlAs

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** right-click **AlGaAs (mat3)** and choose **Duplicate**.

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **AlAs Domain**.



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

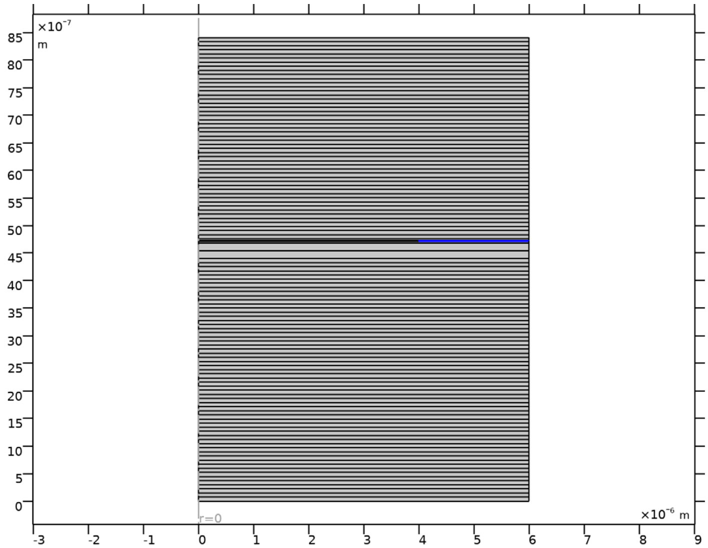
Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	n_AlAs	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

AlOx

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

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **AlOx Domain**.



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

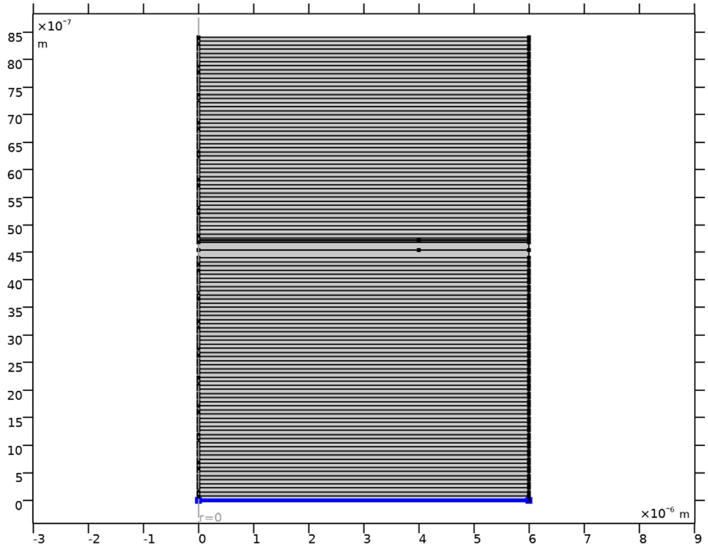
GaAs Substrate

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** right-click **Air Superstrate (mat1)** and choose **Duplicate**.

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

3 Locate the **Geometric Entity Selection** section. Click **Clear Selection**.

4 Select Boundary 2 only, which is the bottom boundary.



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 ; nii = n_iso, nij = 0	n_GaAs	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

DEFINITIONS

Define a variable for the quantum well gain coefficient. This variable will be used by the first physics interface and in the first study. In the second study and for the second physics interface, the quantum well gain coefficient will be self-consistently solved for.

Variables 1

1. In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.
2. In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
kappa_QW	kappa_QW_gain		Refractive index, quantum well, gain domain, imaginary part

MESH 1

Setting up the mesh sequence is again simplified by using the selections defined as part of the geometry sequence.

Free Triangular 1

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

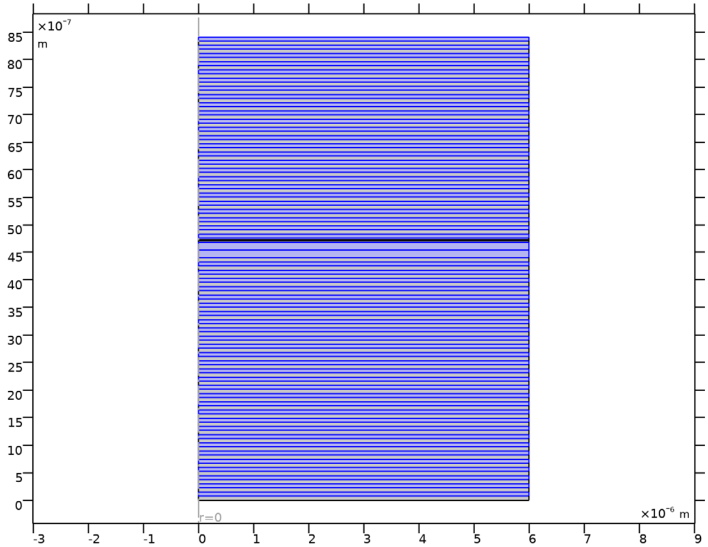
Size

1. In the **Model Builder** window, click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. From the **Predefined** list, choose **Extra coarse**.

GaAs

1. In the **Model Builder** window, right-click **Mesh 1** and choose **Size**.
2. In the **Settings** window for **Size**, type GaAs in the **Label** text field.
3. Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **GaAs Layers**.



5 Locate the **Element Size** section. Click the **Custom** button.

6 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

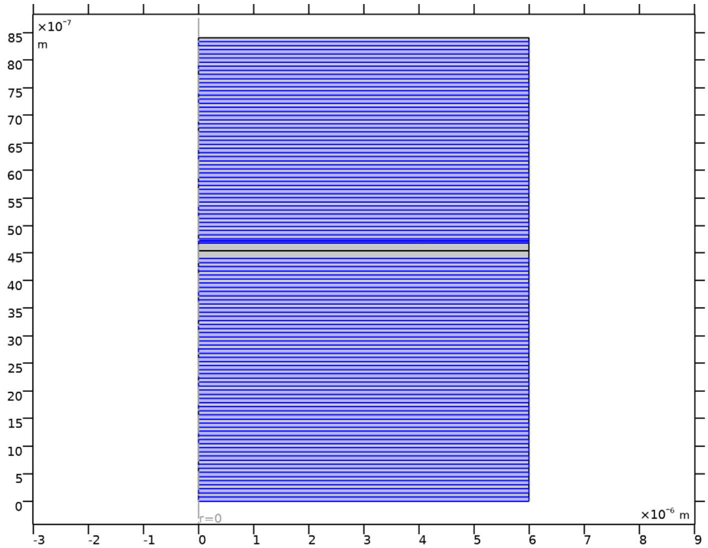
7 In the associated text field, type `lda0/6/n_GaAs`.

AlGaAs

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

2 In the **Settings** window for **Size**, type `AlGaAs` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **AlGaAs Layers**.



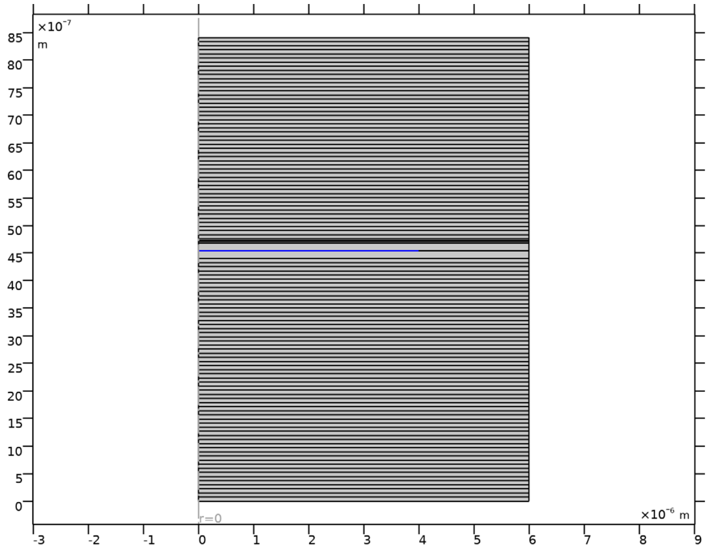
4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `lda0/6/n_AlGaAs`.

QW Gain

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

2 In the **Settings** window for **Size**, type `QW Gain` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **QW Gain Domain**.



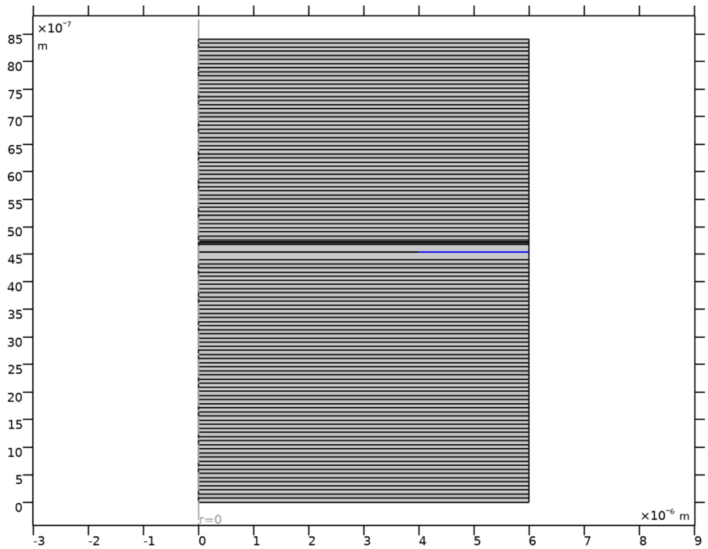
4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `lda0/6/n_QW`.

QW Loss

1 Right-click **QW Gain** and choose **Duplicate**.

2 In the **Settings** window for **Size**, type `QW Loss` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **QW Loss Domain**.

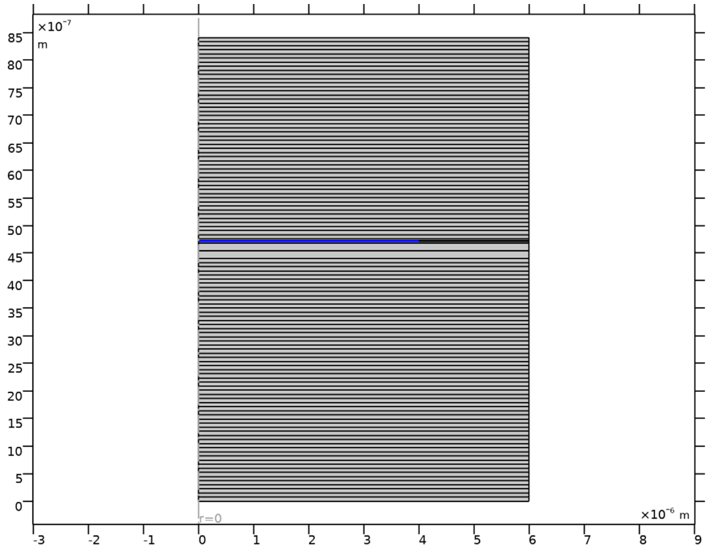


AlAs

1 Right-click **QW Loss** and choose **Duplicate**.

2 In the **Settings** window for **Size**, type `AlAs` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **AlAs Domain**.



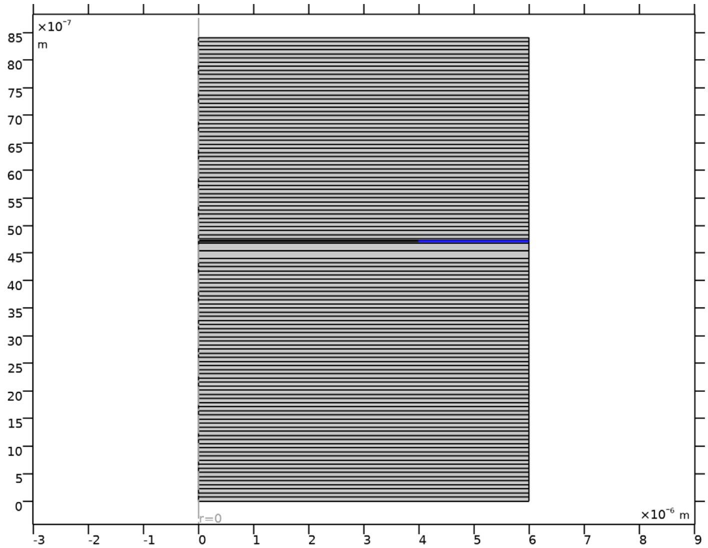
4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `lda0/6/n_AlAs`.

AlOx

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

2 In the **Settings** window for **Size**, type `AlOx` in the **Label** text field.

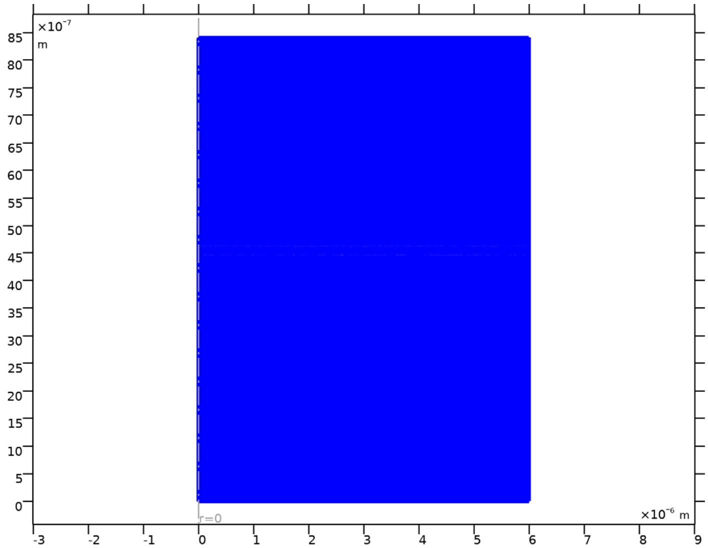
3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **AlOx Domain**.



4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `lda0/6/n_AlOx`.

Free Triangular 1

In the **Model Builder** window, right-click **Free Triangular 1** and choose **Build All**.



STUDY 1

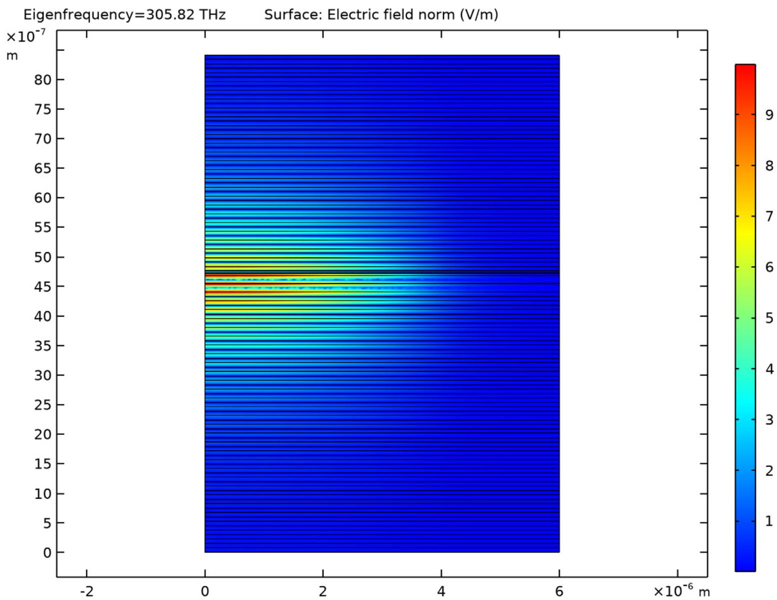
Step 1: Eigenfrequency

1. In the **Model Builder** window, under **Study 1** click **Step 1: Eigenfrequency**.
2. In the **Settings** window for **Eigenfrequency**, locate the **Study Settings** section.
3. Select the **Desired number of eigenfrequencies** check box.
4. In the associated text field, type `1`.
5. In the **Search for eigenfrequencies around** text field, type `f0`.
6. Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** check box.
7. In the **Physics and variables selection** tree, select **Component 1 (comp1)> Electromagnetic Waves, Frequency Domain 2 (ewfd2)**.
8. Click **Disable**. If you don't disable the second physics interface, it will not be possible to rerun this study once the second physics is fully defined as it will also define a variable called `kappa_QW`.
9. In the **Home** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd)

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



This shows that the mode is centered between the top and bottom DBRs and that the field has a non-zero amplitude on the symmetry axis.

Eigenfrequencies (ewfd)

1 In the **Model Builder** window, expand the **Results>Derived Values** node, then click **Eigenfrequencies (ewfd)**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`ewfd.lambda0`	`nm`	`Wavelength in free space`

The wavelength is added to the table in addition to the already existing variables for the frequency `ewfd.freq` and the quality factor `ewfd.Qfactor`.

4 Click **Evaluate**.

The quality factor is a measure of the loss in the system. A higher quality factor, means less loss.

DEFINITIONS

Now define the settings for the second physics interface and the second study.

Start by adding a point integration operator. This operator will be used when normalizing the field.

Point Evaluation

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

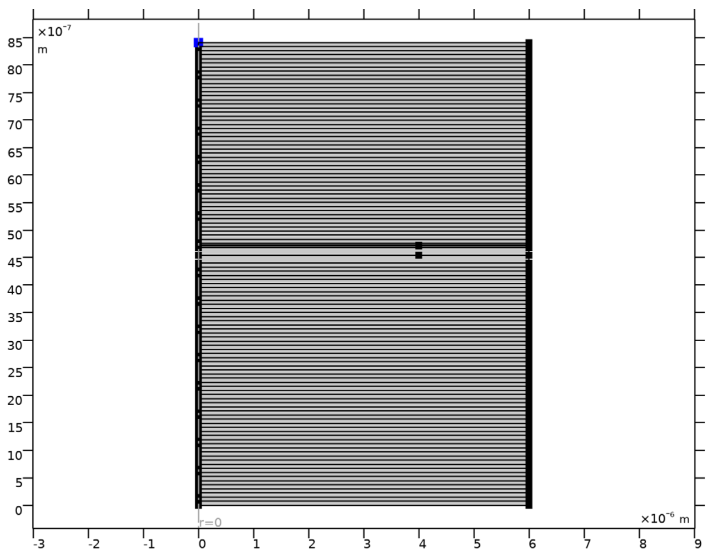
2 In the **Settings** window for **Integration**, type `Point Evaluation` in the **Label** text field.

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

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `115` in the **Selection** text field. This corresponds to the point where the top boundary cross the symmetry axis.

6 Click **OK**.



7 In the **Settings** window for **Integration**, locate the **Advanced** section.

8 From the **Method** list, choose **Summation over nodes**.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN 2 (EWFD2)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain 2 (ewfd2)**.

2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, click to expand the **Equation** section.

3 From the **Equation form** list, choose **Frequency domain**.

4 From the **Frequency** list, choose **User defined**. In the *f* text field, type `freq1`. A dependent variable with this name will later be added.

5 Locate the **Out-of-Plane Wave Number** section. In the *m* text field, type `1`.

Initial Values 1

When later solving for the frequency and the threshold gain, the field solution will be found close to the initial value specified below.

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain 2 (ewfd2)** click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 Specify the $\mathbf{E}2$ vector as

`withsol('sol1',ewfd.Er)`	r
`withsol('sol1',ewfd.Ephi)`	phi
`withsol('sol1',ewfd.Ez)`	z

The `withsol` operator evaluates the provided expression in the second argument, using the solution specified in the first argument.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Impedance Boundary Condition 1, Scattering Boundary Condition 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)**, Ctrl-click to select **Scattering Boundary Condition 1** and **Impedance Boundary Condition 1**.

2 Right-click and choose **Copy**.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN 2 (EWFD2)

Scattering Boundary Condition 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Electromagnetic Waves, Frequency Domain 2 (ewfd2)** and choose **Paste Multiple Items**.

To be able to add **Global Equations** nodes, you must first enable **Equation-Based Contributions** from the **Show More Options** dialog.

2 Click the **Show More Options** button in the **Model Builder** toolbar.

3 In the **Show More Options** dialog box, in the tree, select the check box for the node **Physics>Equation-Based Contributions**.

4 In the tree, select the check box for the node **Physics>Advanced Physics Options**.

5 Click **OK**.

Now, you are ready to add **Global Equations** nodes.

Frequency

1 In the **Physics** toolbar, click **Global** and choose **Global Equations**.

2 In the **Settings** window for **Global Equations**, type `Frequency` in the **Label** text field.

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

Name	f(u,ut,utt,t) (1)	Initial value (u_0) (1)	Initial value (u_t0) (1/s)	Description
`freq1`	`intop1(real(withsol('sol1', ewfd.Er)))-intop1(real(ewfd2.Er))`	`withsol('sol1', ewfd.freq)`	`0`	`Frequency`

Here, the previously defined point integration operator is used to normalize the real part of a field value to a specified value in the point the operator was defined for. The `withsol` operator is again used for evaluating an expression from the first physics using a solution from the first study.

4 Click to expand the **Discretization** section. From the **Value type when using splitting of complex variables** list, choose **Real**, as the frequency is a real quantity.

5 Locate the **Units** section. Click **Select Dependent Variable Quantity**.

6 In the **Physical Quantity** dialog box, type `frequency` in the text field.

7 Click **Filter**.

8 In the tree, select **General>Frequency (Hz)**.

9 Click **OK**.

10 In the **Settings** window for **Global Equations**, locate the **Units** section.

11 Click **Select Source Term Quantity**.

12 In the **Physical Quantity** dialog box, type `electric` in the text field.

13 Click **Filter**.

14 In the tree, select **Electromagnetics>Electric field (V/m)**.

15 Click **OK**.

Gain

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

2 In the **Settings** window for **Global Equations**, type `Gain` in the **Label** text field.

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

Name	f(u,ut,utt,t) (V/m)	Initial value (u_0) (Hz)	Initial value (u_t0) (Hz/s)	Description
kappa_QW	intop1(imag(withsol('sol1', ewfd.Er)))-intop1(imag(ewfd2.Er))	kappa_QW_gain	0	Refractive index, QW, imaginary part

Here, the imaginary part of the field value in the point defined by the integration operator is set to a specified value.

4 Locate the **Units** section. Click **Select Dependent Variable Quantity**.

5 In the **Physical Quantity** dialog box, type `dimension` in the text field.

6 Click **Filter**.

7 In the tree, select **General>Dimensionless (1)**.

8 Click **OK**.

Also the `kappa_QW` variable will be a real variable.

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 **Empty Study**.

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

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

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

STUDY 2

Stationary

1 In the **Study** toolbar, click **Study Steps** and choose **Stationary>Stationary**.

2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

3 Select the **Modify model configuration for study step** check box.

4 In the **Physics and variables selection** tree, select **Component 1 (comp1)>Definitions> Variables 1**.

5 Click **Disable**, to avoid that the previously defined kappa_QW variable will be used in this study.

6 In the **Physics and variables selection** tree, select **Component 1 (comp1)> Electromagnetic Waves, Frequency Domain (ewfd)**.

7 Click **Disable**.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**, to be able to edit the solver sequence.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node, then click **Compile Equations: Stationary**.

3 In the **Settings** window for **Compile Equations**, locate the **Study and Step** section.

4 Select the **Split complex variables in real and imaginary parts** check box. This will make sure that the real variables defined in the **Global Equations** will be treated correctly when solving.

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

RESULTS

Height Expression 1

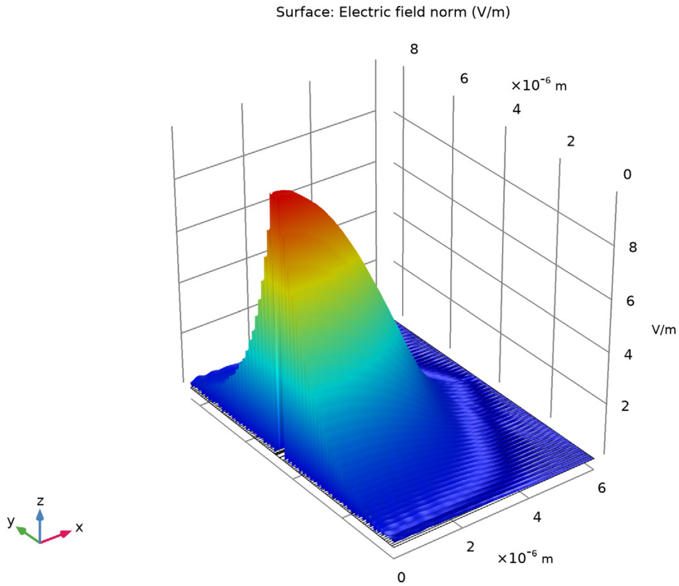
1 In the **Model Builder** window, expand the **Results>Electric Field (ewfd2)** node.

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

3 Right-click **Height Expression 1** and choose **Show Legends**.

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

5 In the **Electric Field (ewfd2)** toolbar, click **Plot**.



Using the **Height Expression** makes the mode field distribution clearer.

Gain Evaluation

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

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

Expression	Unit	Description
freq1	THz	Frequency
c_const/freq1	nm	Wavelength
kappa_QW	1	Refractive index, QW, imaginary part
-2*kappa_QW*k0	1/cm	Threshold material gain

5 Click **Evaluate**.

The wavelength and the threshold material gain values agree well with the results in Figs. 2 and 3 of Ref. 1 for oxide position 3.

Appendix: Geometry Modeling Instructions

The following instructions will build the VCSEL geometry and define some useful selections.

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **2D Axisymmetric**.

2 Click **Done**.

GLOBAL DEFINITIONS

Geometry Parameters

Start by adding some parameters defining the geometry.

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, type `Geometry Parameters` in the **Label** text field.

3 Locate the **Parameters** section. Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `vertical_cavity_surface_emitting_laser_geometry_parameters.txt`.

Add a part representing a pair of high- and low-index layers. This part will be used when building the mirror stacks for the laser.

5 Right-click **Global Definitions>Geometry Parameters** and choose **2D Part**.

DBR PAIR

1 In the **Settings** window for **Part**, type `DBR Pair` in the **Label** text field.

2 Locate the **Input Parameters** section. Click **Load from File**.

3 Browse to the model's Application Libraries folder and double-click the file `vertical_cavity_surface_emitting_laser_dbr_pair_parameters.txt`.

Bottom Layer

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

2 In the **Settings** window for **Rectangle**, type `Bottom Layer` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `w`.

4 In the **Height** text field, type `d1`.

5 Locate the **Position** section. In the **x** text field, type `pos_x`.

6 In the **y** text field, type `pos_y`.

7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

8 From the **Color** list, choose **Color 8**.

Top Layer

1 Right-click **Bottom Layer** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `Top Layer` in the **Label** text field.

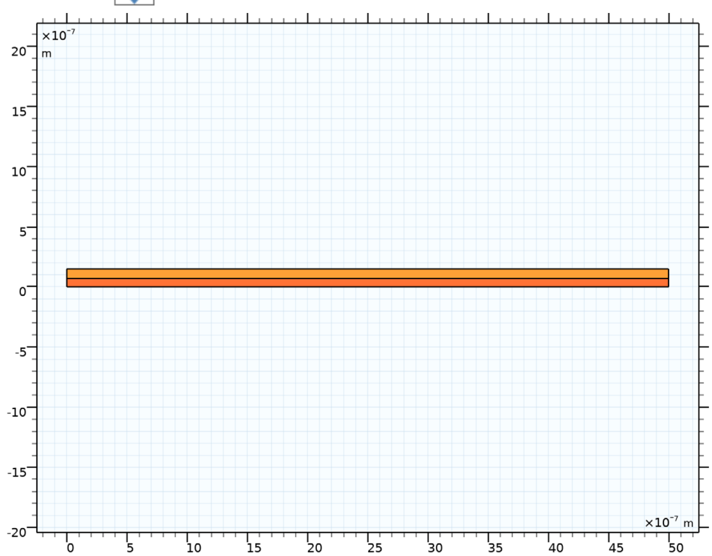
3 Locate the **Size and Shape** section. In the **Height** text field, type `d2`.

4 Locate the **Position** section. In the **y** text field, type `pos_y+d1`.

5 Locate the **Selections of Resulting Entities** section. From the **Color** list, choose **Color 18**.

6 In the **Geometry** toolbar, click **Build All**.

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



GEOMETRY 1

Now, use the part to start building the bottom mirror.

DBR Pair 1 (pi1)

1 In the **Geometry** toolbar, click **Parts** and choose **DBR Pair**.

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
d1	t_AlGaAs_DBR	7.963E-8 m	Thickness, bottom layer
d2	t_GaAs_DBR	6.949E-8 m	Thickness, toplayer
w	d_outer/2	6E-6 m	Width

4 Click to expand the **Domain Selections** section. Click to select row number 1 in the table.

5 Click **New Cumulative Selection**.

6 In the **New Cumulative Selection** dialog box, type AlGaAs Layers in the **Name** text field. The cumulative selections will later be used when assigning the materials and when building the mesh sequence.

7 Click **OK**.

8 In the **Settings** window for **Part Instance**, locate the **Domain Selections** section.

9 Click to select row number 2 in the table.

10 Click **New Cumulative Selection**.

11 In the **New Cumulative Selection** dialog box, type GaAs Layers in the **Name** text field.

12 Click **OK**.

Bottom DBR

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

2 In the **Settings** window for **Array**, type Bottom DBR in the **Label** text field.

3 Click in the **Graphics** window and then press Ctrl+A to select both objects.

4 Locate the **Size** section. From the **Array type** list, choose **Linear**.

5 In the **Size** text field, type N_bottom_DBR.

6 Locate the **Displacement** section. In the **z** text field, type t_DBR_pair.

7 Click **Build All Objects**.

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

In the following instructions, you will see many **Build All Objects** instructions followed by a **Zoom Extents** instructions. Performing those steps will help you display your progress, when building the VCSEL geometry. However, they are not necessary for building a correct geometry.

Top Layer in Bottom DBR

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

2 In the **Settings** window for **Rectangle**, type `Top Layer in Bottom DBR` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `d_outer/2`.

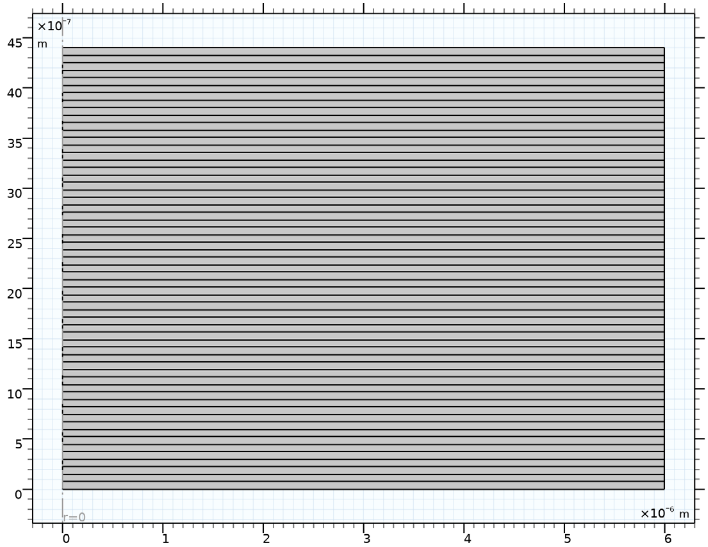
4 In the **Height** text field, type `t_AlGaAs_DBR`.

5 Locate the **Position** section. In the **z** text field, type `N_bottom_DBR*t_DBR_pair`.

6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **AlGaAs Layers**.

7 Click **Build All Objects**.

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



Bottom GaAs Layer in Lambda Cavity

1 Right-click **Top Layer in Bottom DBR** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `Bottom GaAs Layer in Lambda Cavity` in the **Label** text field.

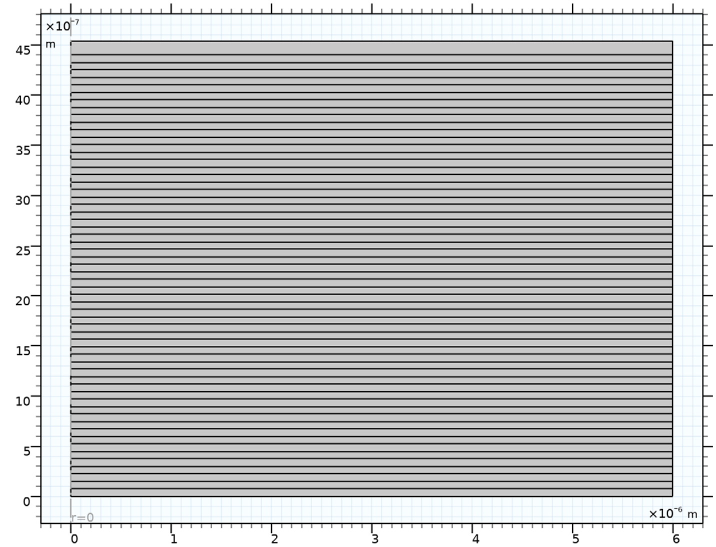
3 Locate the **Size and Shape** section. In the **Height** text field, type `t_GaAs_cavity`.

4 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR`.

5 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. From the **Contribute to** list, choose **GaAs Layers**.

6 Click **Build All Objects**.

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



QW Gain Domain in Lambda Cavity

1 Right-click **Bottom GaAs Layer in Lambda Cavity** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `QW Gain Domain in Lambda Cavity` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `d_oxide/2`.

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

5 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR+t_GaAs_cavity`.

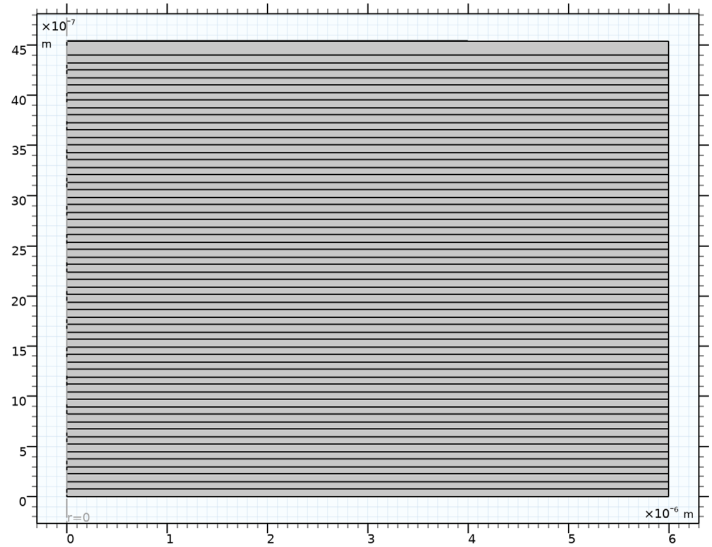
6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

7 In the **New Cumulative Selection** dialog box, type `QW Gain Domain` in the **Name** text field.

8 Click **OK**.

9 In the **Settings** window for **Rectangle**, click **Build All Objects**.

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



QW Loss Domain in Lambda Cavity

1 Right-click **QW Gain Domain in Lambda Cavity** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `QW Loss Domain in Lambda Cavity` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `(d_outer-d_oxide)/2`.

4 Locate the **Position** section. In the **r** text field, type `d_oxide/2`.

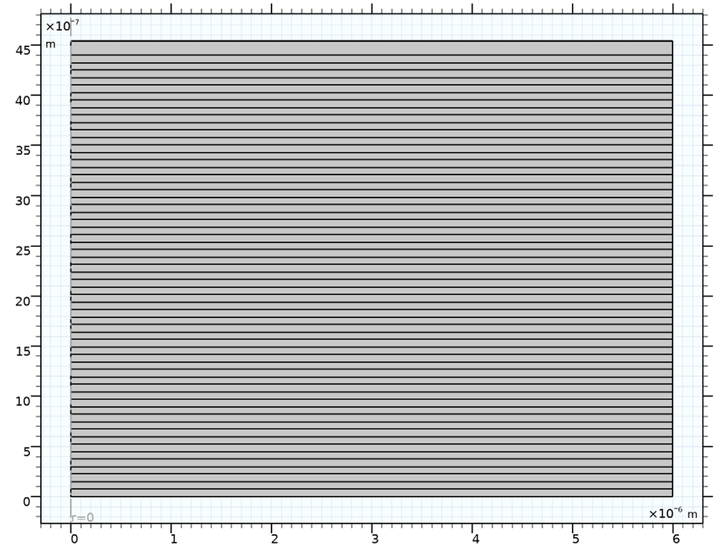
5 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

6 In the **New Cumulative Selection** dialog box, type `QW Loss Domain` in the **Name** text field.

7 Click **OK**.

8 In the **Settings** window for **Rectangle**, click **Build All Objects**.

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



Top GaAs Layer in Lambda Cavity

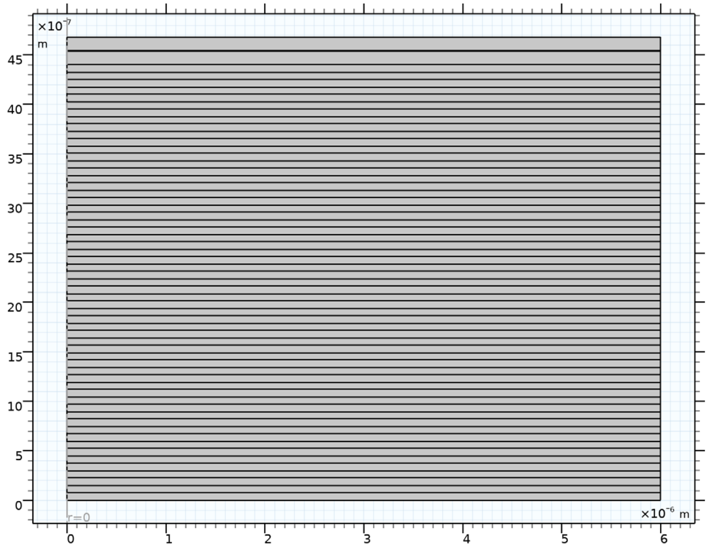
1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Bottom GaAs Layer in Lambda Cavity (r2)** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `Top GaAs Layer in Lambda Cavity` in the **Label** text field.

3 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR+t_GaAs_cavity+t_QW`.

4 Click **Build All Objects**.

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



A layer with zero thickness cannot be added to the geometry sequence. Thus, enclose this layer within an if statement.

If Bottom AlGaAs Layer in Oxide Window is Finite

1 In the **Geometry** toolbar, click **Programming** and choose **If + End If**.

2 In the **Settings** window for **If**, type `If Bottom AlGaAs Layer in Oxide Window is Finite` in the **Label** text field.

3 Locate the **If** section. In the **Condition** text field, type `t_AlGaAs_oxide_window_bottom_layer>0`.

Bottom AlGaAs Layer in Oxide Window

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Top Layer in Bottom DBR (r1)** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `Bottom AlGaAs Layer in Oxide Window` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Height** text field, type `t_AlGaAs_oxide_window_bottom_layer`.

4 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR+t_cavity`.

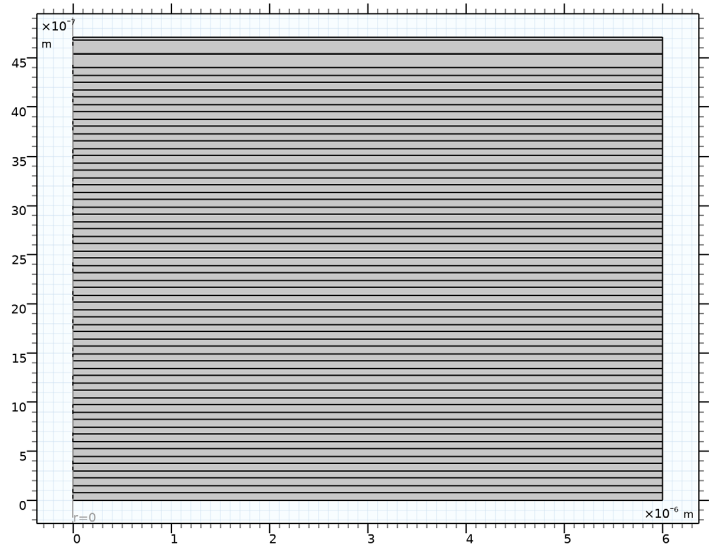
End If Bottom AlGaAs Layer in Oxide Window is Finite

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **End If 1 (endif1)**.

2 In the **Settings** window for **End If**, type `End If Bottom AlGaAs Layer in Oxide Window is Finite` in the **Label** text field.

3 Click **Build All Objects**.

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



AlAs Domain in Oxide Window

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Bottom AlGaAs Layer in Oxide Window (r6)** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `AlAs Domain in Oxide Window` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `d_oxide/2`.

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

5 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR+t_cavity+ t_AlGaAs_oxide_window_bottom_layer`.

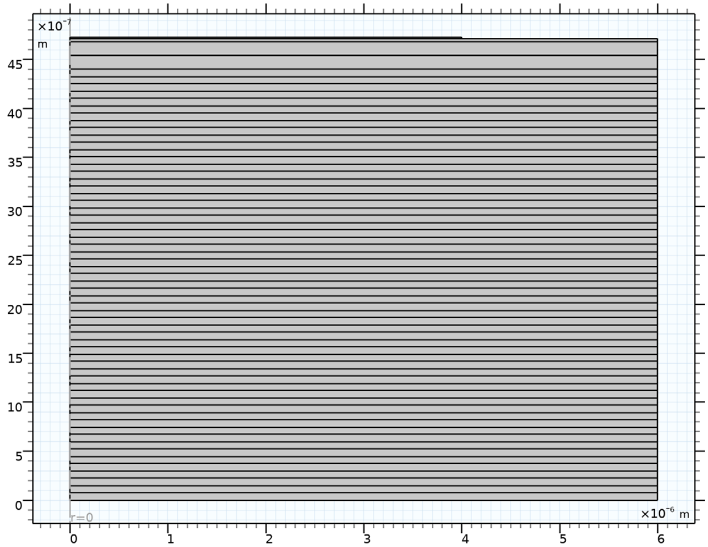
6 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

7 In the **New Cumulative Selection** dialog box, type `AlAs Domain` in the **Name** text field.

8 Click **OK**.

9 In the **Settings** window for **Rectangle**, click **Build All Objects**.

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



AlOx Domain in Oxide Window

1 Right-click **AlAs Domain in Oxide Window** and choose **Duplicate**.

2 In the **Settings** window for **Rectangle**, type `AlOx Domain in Oxide Window` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `(d_outer-d_oxide)/2`.

4 Locate the **Position** section. In the **r** text field, type `d_oxide/2`.

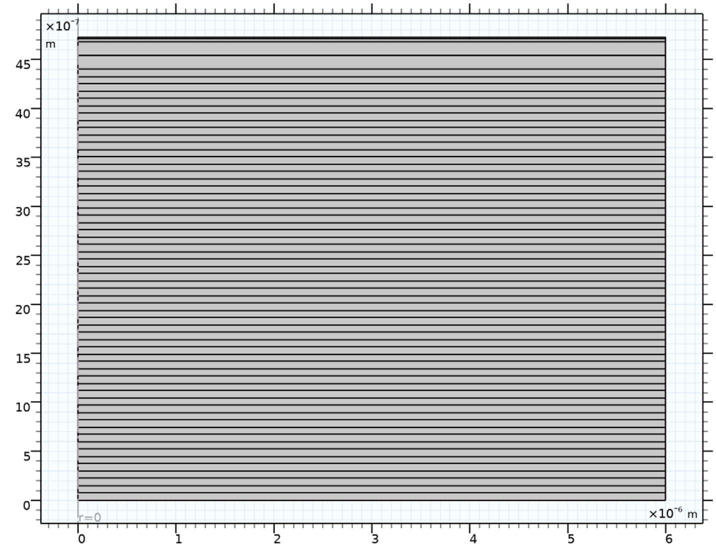
5 Locate the **Selections of Resulting Entities** section. Find the **Cumulative selection** subsection. Click **New**.

6 In the **New Cumulative Selection** dialog box, type `AlOx Domain` in the **Name** text field.

7 Click **OK**.

8 In the **Settings** window for **Rectangle**, click **Build All Objects**.

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



Bottom AlGaAs Layer in Oxide Window (r6), End If Bottom AlGaAs Layer in Oxide Window is Finite (endif1), If Bottom AlGaAs Layer in Oxide Window is Finite (if1)

In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1**, Ctrl-click to select **If Bottom AlGaAs Layer in Oxide Window is Finite (if1)**, **Bottom AlGaAs Layer in Oxide Window (r6)**, and **End If Bottom AlGaAs Layer in Oxide Window is Finite (endif1)**.

If Second AlGaAs Layer in Oxide Window is Finite

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

2 In the **Settings** window for **If**, type `If Second AlGaAs Layer in Oxide Window is Finite` in the **Label** text field.

3 Locate the **If** section. In the **Condition** text field, type `t_AlGaAs_oxide_window_second_layer>0`.

Second AlGaAs Layer in Oxide Window

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Bottom AlGaAs Layer in Oxide Window 1 (r9)**.

2 In the **Settings** window for **Rectangle**, type `Second AlGaAs Layer in Oxide Window` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Height** text field, type `t_AlGaAs_oxide_window_second_layer`.

4 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR+t_cavity+t_AlGaAs_oxide_window_bottom_layer+t_oxide`.

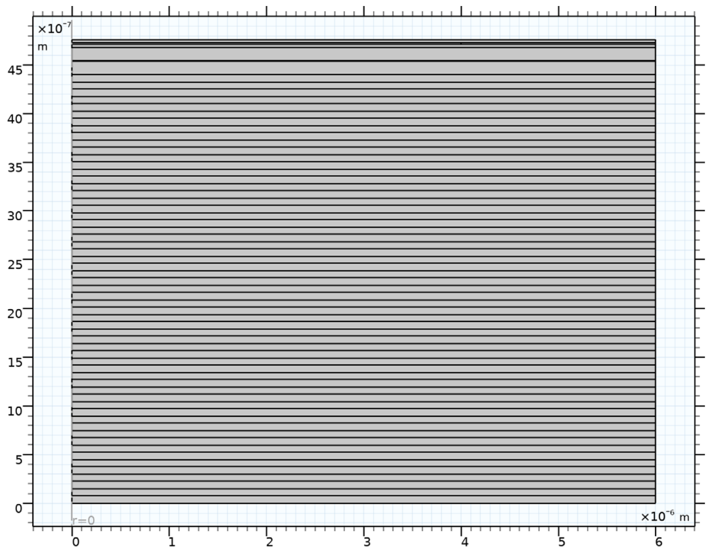
End If Second AlGaAs Layer in Oxide Window is Finite

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **End If Bottom AlGaAs Layer in Oxide Window is Finite 1 (endif2)**.

2 In the **Settings** window for **End If**, type `End If Second AlGaAs Layer in Oxide Window is Finite` in the **Label** text field.

3 Click **Build All Objects**.

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



Top GaAs Layer in Oxide Window

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Bottom GaAs Layer in Lambda Cavity (r2)** and choose **Duplicate**.

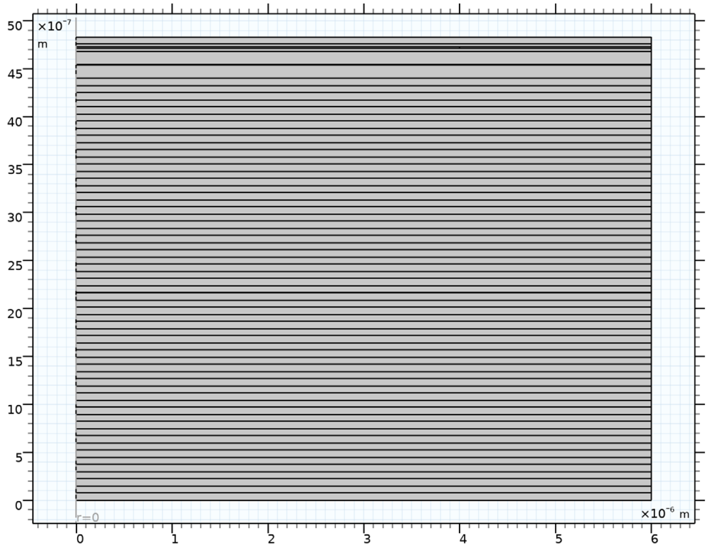
2 In the **Settings** window for **Rectangle**, type `Top GaAs Layer in Oxide Window` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Height** text field, type `t_GaAs_DBR`.

4 Locate the **Position** section. In the **z** text field, type `t_bottom_DBR+t_cavity+t_AlGaAs_oxide_window_bottom_layer+t_oxide+t_AlGaAs_oxide_window_second_layer`.

5 Click **Build All Objects**.

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



DBR Pair 2 (pi2)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **DBR Pair 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
pos_y	`t_bottom_DBR+ t_cavity+ t_oxide_window`	4.8312E-6 m	Vertical position

Top DBR

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

2 In the **Settings** window for **Array**, type `Top DBR` in the **Label** text field.

3 Select the objects **pi2(1)** and **pi2(2)** only.

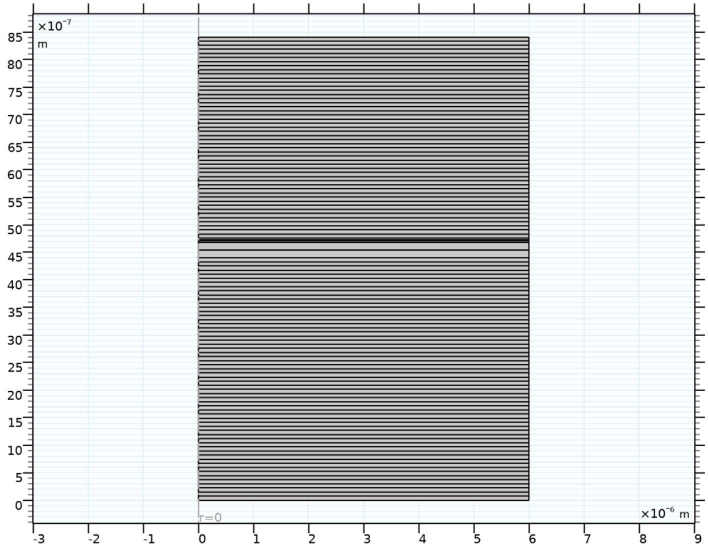
4 Locate the **Size** section. From the **Array type** list, choose **Linear**.

5 In the **Size** text field, type `N_top_DBR`.

6 Locate the **Displacement** section. In the **z** text field, type `t_DBR_pair`.

7 Click **Build All Objects**.

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



This completes the set up of the geometry sequence.