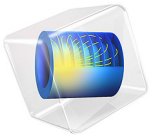


In-Plane Switching of a Liquid Crystal Cell

Introduction

Liquid crystals (LCs) are liquid organic materials showing a certain degree of ordering, either positional and/or orientational.

Many types of liquid-crystal materials exist, like nematic, smectic, and cholesteric. Both nematic and smectic LCs line up in the same direction. However, smectic LCs form layers of aligned molecules, whereas nematic LCs do not. For cholesteric LCs, on the other hand, the molecules align in thin layers, but each layer has a slightly different orientation relative the neighboring layers.

Most of the applications for LCs are related to displays. Examples are screens for TVs, laptops, and mobile phones. Other nondisplay applications are laser beam steering and wavelength tunable filters.

Nematic LCs can be used in many different configuration. Typically the LC material is placed between a polarizer and an analyzer. The polarizer and analyzer only transmit light having linear polarization in a certain direction. For most cases, the polarizer and the analyzer polarization directions are orthogonal. So, unless the LC material rotates the polarization of the electromagnetic wave passing through it, the total transmittance through the device will be very low. This configuration is the normally-black mode. However, if the LC material rotates the polarization plane of the transmitted wave by 90 degrees, the device will be configured in the normally-white mode.

In LC devices, the surfaces next to the liquid crystal are rubbed to align the molecules in a specific direction. It is said that the molecules are anchored to the adjacent boundary.

For twisted nematic LC cells, the molecules are anchored to the two opposing boundaries at an angle of 90 degrees. Thus, without any applied field, the molecules in the LC will spiral around axes that are aligned between the top and bottom boundaries. An input wave, with a polarization aligned with the anchoring angle at the LC entrance boundary, will have its polarization plane rotate 90 degrees as the wave propagates through the LC layer. Thereby, the analyzer will transmit the wave and the device operates in the normally-white mode.

For a twisted nematic LC cell, the transmittance is controlled by applying a voltage difference between the top and bottom boundaries. When the electric field is large enough, the molecules will align with the electric field, and thereby the polarization plane for the optical wave will no longer rotate as the wave passes the LC layer. Then the analyzer will block the wave and the pixel will appear black.

For nonnormal propagation, the zero-field polarization rotation will be smaller and thereby the pixel will appear less white. Thus, a problem with twisted nematic LC displays is that they have a limited viewing angle.

To improve the viewing angle, many new LC display configurations have been invented. In this model, the in-plane switching (IPS) configuration will be used. Here, the anchoring angles for the top and bottom boundaries are the same, forming a nominally-black configuration.

In the IPS configuration, the control electrodes are placed on the same boundary. Thus, when a voltage is applied to one of the electrodes, the electric field between the electrodes will be parallel to the boundaries. This will make the molecules rotate to follow the electric field direction. Now, when the optical wave passes through the LC layer, the polarization state will change so a substantial part of the wave will be transmitted through the analyzer.

Model Definition

In this model, the Oseen–Frank theory for the liquid crystal material will be used. The starting point for this theory is that the local molecule directions in the liquid crystal can be described by a unit vector $\mathbf{n}(\mathbf{r})$ — the director field.

Since this director field is of unit length, two angles can parameterize the vector field,

$$\mathbf{n}(\mathbf{r}) = (\cos\theta\cos\varphi, \sin\theta\cos\varphi, \sin\varphi)\,.$$

The director field is used in the Oseen–Frank free energy density for nematic LCs,

$$F(\mathbf{n}, \nabla\mathbf{n}) = \frac{1}{2}K_{11}(\nabla\cdot\mathbf{n})^2 + \frac{1}{2}K_{22}(\mathbf{n}\cdot\nabla\times\mathbf{n})^2 + \frac{1}{2}K_{33}|\mathbf{n}\times\nabla\times\mathbf{n}|^2\,.$$

Here, K_{11}, K_{22}, and K_{33} are the Frank elastic constants describing the splay, twist, and bend contributions, respectively. The values for these constants depend on the particular material, but have values of the order of 1 pN.

When an electric field is applied, the electric energy density,

$$F_E = \frac{1}{2}\mathbf{D}\cdot\mathbf{E}$$

is subtracted from the elastic free energy. Here, $\mathbf{D}$ is the electric displacement field, defined by

$$\mathbf{D} = \varepsilon_0 \varepsilon_r \mathbf{E}$$

$$= \varepsilon_0 \begin{bmatrix} \varepsilon_\perp(1-n_x n_x)+\varepsilon_{||} n_x n_x & (\varepsilon_{||}-\varepsilon_\perp) n_x n_y & (\varepsilon_{||}-\varepsilon_\perp) n_x n_z \\ (\varepsilon_{||}-\varepsilon_\perp) n_x n_y & \varepsilon_\perp(1-n_y n_y)+\varepsilon_{||} n_y n_y & (\varepsilon_{||}-\varepsilon_\perp) n_y n_z \\ (\varepsilon_{||}-\varepsilon_\perp) n_x n_z & (\varepsilon_{||}-\varepsilon_\perp) n_y n_z & \varepsilon_\perp(1-n_z n_z)+\varepsilon_{||} n_z n_z \end{bmatrix} \mathbf{E}$$

Here, $\varepsilon_\perp$ and $\varepsilon_{||}$ are the relative permittivity values when the field is orthogonal or parallel to the director direction, respectively. This equation represents the electric displacement field for the statically applied electric field.

The relative permittivity is also anisotropic for the optical field. In this case, the orthogonal value is called the relative permittivity for ordinary polarization and the parallel value is called the relative permittivity for the extraordinary polarization.

To solve for the director field and the electrostatic field, a **Weak Form PDE** interface is used for minimizing the energies and the **Electrostatics** interface is used for solving for the electric potential. Solving for the director field and the electric potential is done self-consistently, forming a nonlinear equation system.

The weak expression used for minimizing the free energy is `test(F)-var(es.W,theta,phi)`. COMSOL Multiphysics integrates this expression over the LC domain and the `test` and `var` operators take the derivatives of the degrees of freedom for the dependent variables — the angles `theta` and `phi` — to find the equations that minimizes the energy. Here, `F` is the Oseen–Frank free energy density, previously defined, and `es.W` is the electric energy density, as defined by the **Electrostatics** interface (having the tag `es`). The reason `test` is used in the first term and `var` is used in the second term, is because we only want to take the derivatives with respect to the degrees of freedom for the director angles. If we would have used the `test` operator also on `es.W`, also the derivatives of the degrees of freedom for the electric potential would have been included. However, with the `var` operator, it is possible to specify with respect to what dependent variables you would like to perform the derivatives.

The model is inspired by the IPS device discussed in Ref. 1.

Figure 1 shows the distribution of the director field in the LC. At 5 V, the field in the region between the electrodes is almost tangential to the top and bottom boundaries. This makes the directors rotate in that region and almost align with the electric field direction.

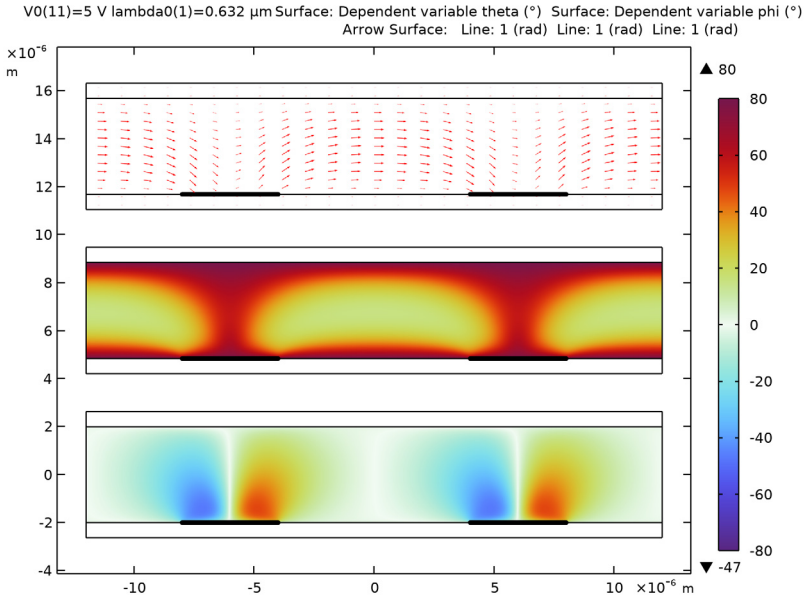


Figure 1: The arrow plot at the top shows the x and y components of the director field. The middle surface plot shows the distribution of the angle `phi` *and the bottom plot shows the distribution of the angle* `theta`*. The applied voltage is 5 V.*

The 3D plot in Figure 2 more clearly shows how the directors rotates and almost align with the applied electric field in the region between the electrodes.

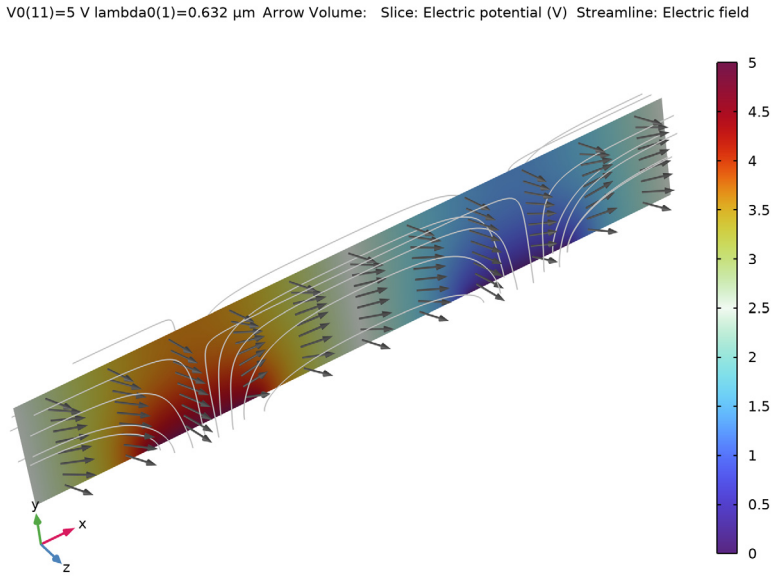


Figure 2: This 3D plot shows the director distribution (gray arrows). The slice plot shows the electric potential distribution and the stream lines follow the electric field. The applied voltage is 5 V.

Figure 3 shows the electric field of the optical wave when no voltage is applied. As there is no change of the polarization state, when the wave propagates through the LC layer, the

analyzer, oriented at an angle of 90 degrees relative the polarizer, will absorb all light. Thus, this device operates in a normally-black mode.

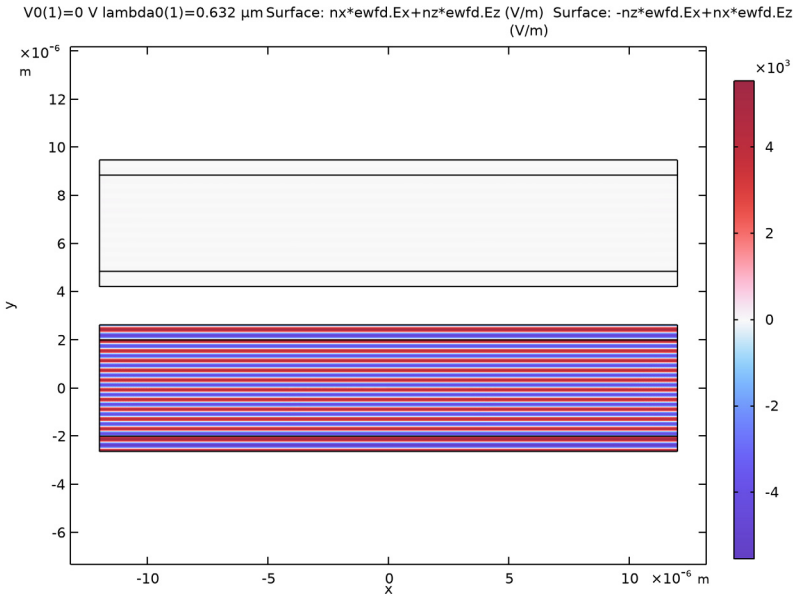


Figure 3: The bottom plot shows the electric field component for the same polarization as the input wave. The top plot shows the electric field component for a polarization that is orthogonal to the input wave polarization. No voltage is applied.

In Figure 4, the applied voltage is 5 V. Now, it is clear that the field with an orthogonal polarization relative the input field (top) is strong. Thus, a large change of the polarization state happens when the wave passes the LC.

The field is not uniform in the *x* direction. This indicates that diffraction to higher-order modes appear, due to the inhomogeneous refractive index distribution.

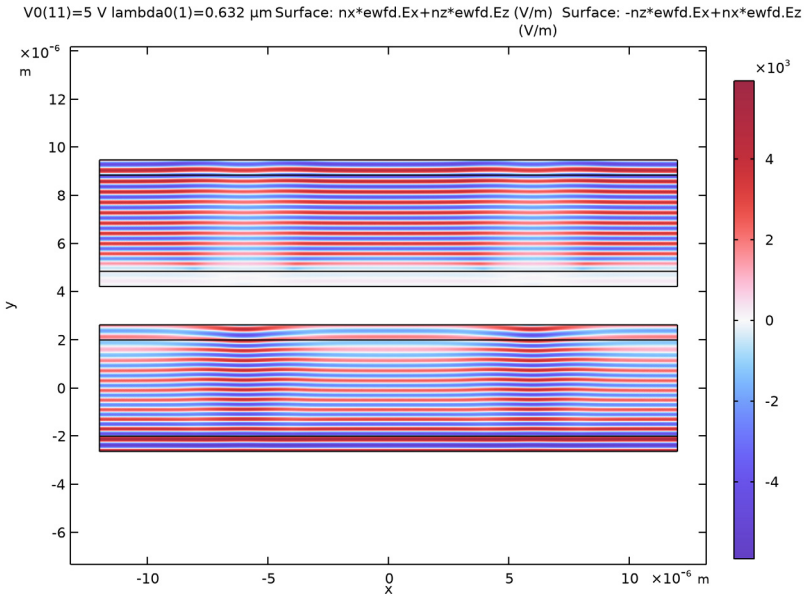


Figure 4: A similar plot as in Figure 3*, but now the applied voltage is 5 V.*

The behavior displayed in Figure 3 and Figure 4 is also confirmed when inspecting the transmittances in Figure 5. The transmittance for the field component having the same polarization as the input wave decreases with an increasing applied potential, whereas the transmittance for the field component with a polarization orthogonal to the input wave increases with increasing applied potential. In addition, the diffraction due to higher-order modes with increasing applied potential is also noticeable from the red curve.

As the analyzer is aligned with the direction orthogonal to the input wave polarization, the transmittance for the device can change from a very low value at zero applied voltage to a

fairly high value at the higher applied voltages. Thereby, this device can have a high dynamic range.

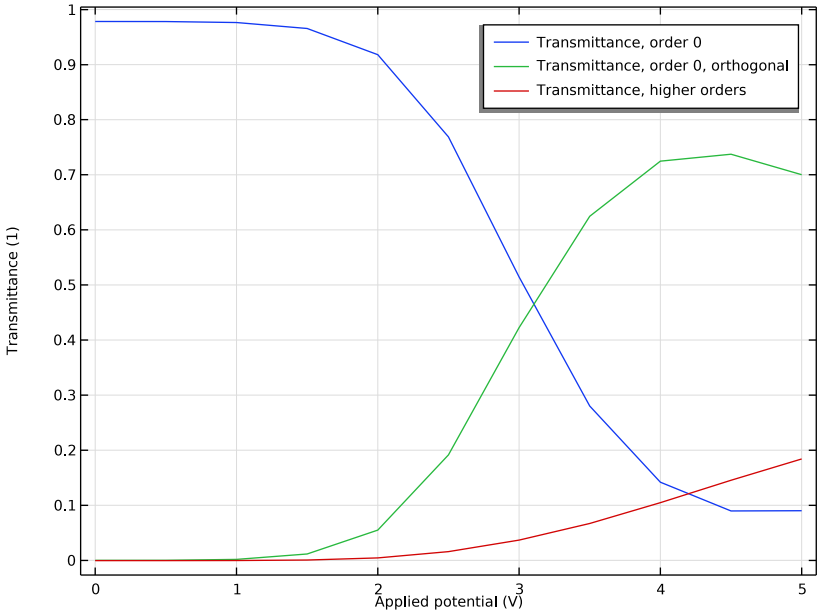


Figure 5: The transmittance for the wave having the same polarization as the input wave (blue) and the transmittance for the wave having a polarization orthogonal to the input wave (green). The red curve displays diffraction to higher-order modes, propagating in nonnormal directions.

Reference

1. R. Lu and others, "Ultrawide-View Liquid Crystal Displays," *J. Displ. Technol.*, vol. 1, no. 1, pp. 3–14, 2005.

Application Library path: `Wave_Optics_Module/Modulators_and_Switches/in_plane_switching_liquid_crystal_cell`

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 **Mathematics>PDE Interfaces>Weak Form PDE (w)**.

3 Click **Add**.

4 In the **Select Physics** tree, select **AC/DC>Electric Fields and Currents>Electrostatics (es)**.

5 Click **Add**.

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

7 Click **Add**.

8 Click **Study**.

9 In the **Select Study** tree, select **Preset Studies for Some Physics Interfaces>Stationary**.

10 Click **Done**.

GLOBAL DEFINITIONS

Next, load some parameters that define the material properties and the geometry from files.

General Parameters

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

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 `in_plane_switching_liquid_crystal_cell_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 `in_plane_switching_liquid_crystal_cell_material_parameters.txt`.

Geometry Parameters

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

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 `in_plane_switching_liquid_crystal_cell_geometry_parameters.txt`.

GEOMETRY 1

Now, add the geometry, consisting of a rectangle representing the liquid crystal layer and the surrounding glass layers. Furthermore, polygons are used for representing the electrodes.

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 `width`.

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

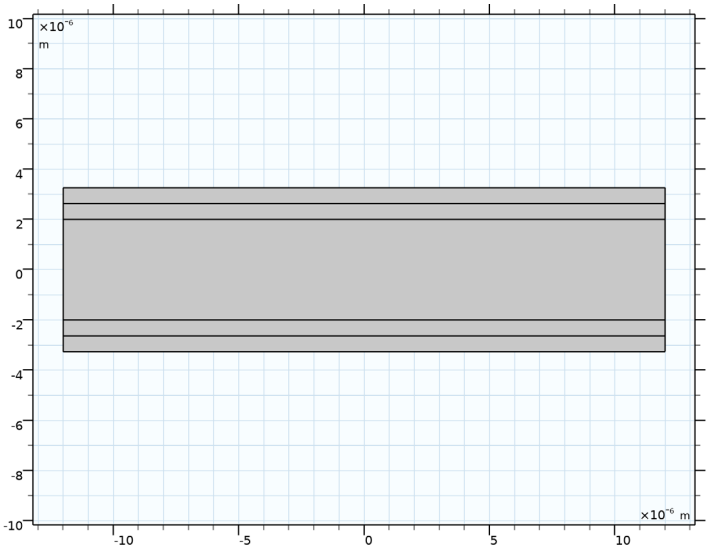
5 Locate the **Position** section. From the **Base** list, choose **Center**.

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

Layer name	Thickness (m)
Layer 1	t_PML
Layer 2	t_glass

7 Select the **Layers on top** check box.

8 Click **Build All Objects**.



Polygon 1 (pol1)

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

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 In the table, enter the following settings:

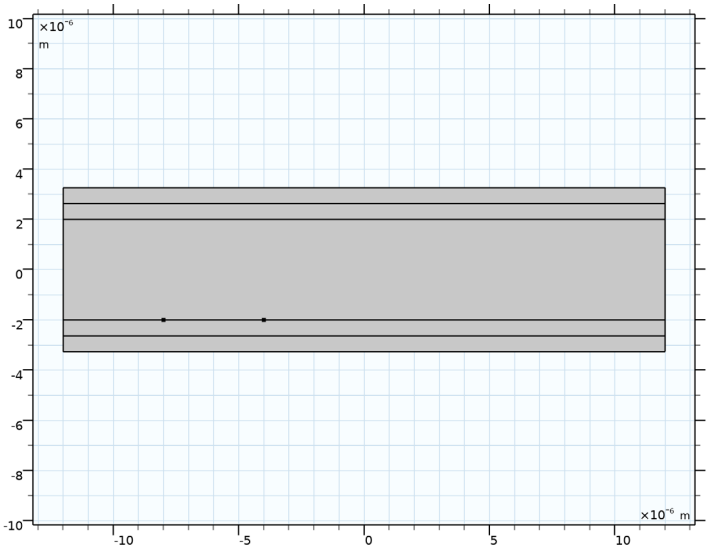
x (m)	y (m)
-d_12/2-d_1	-t_LC/2
-d_12/2	-t_LC/2

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

5 In the **New Cumulative Selection** dialog box, type `Electric Potential` in the **Name** text field.

6 Click **OK**.

7 In the **Settings** window for **Polygon**, click **Build Selected**.



8 Right-click **Polygon 1 (pol1)** and choose **Duplicate**.

Polygon 2 (pol2)

1 In the **Model Builder** window, click **Polygon 2 (pol2)**.

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 In the table, enter the following settings:

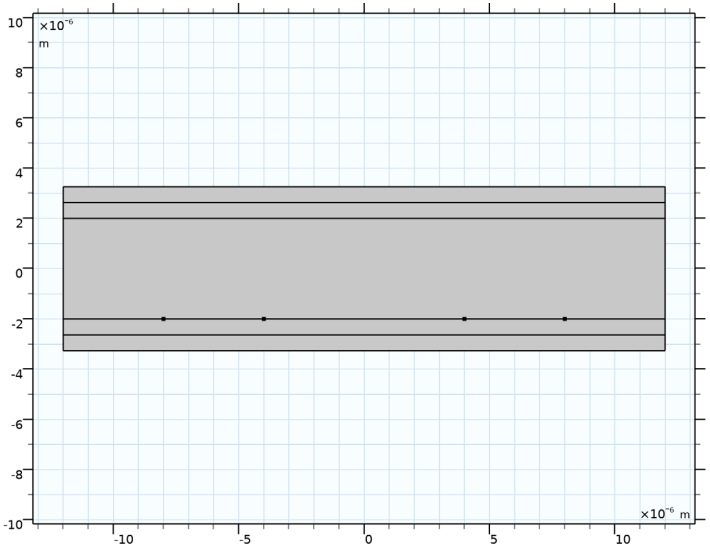
x (m)	y (m)
d_12/2	-t_LC/2
d_12/2+d_2	-t_LC/2

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

5 In the **New Cumulative Selection** dialog box, type Ground in the **Name** text field.

6 Click **OK**.

7 In the **Settings** window for **Polygon**, click **Build All Objects**.



DEFINITIONS

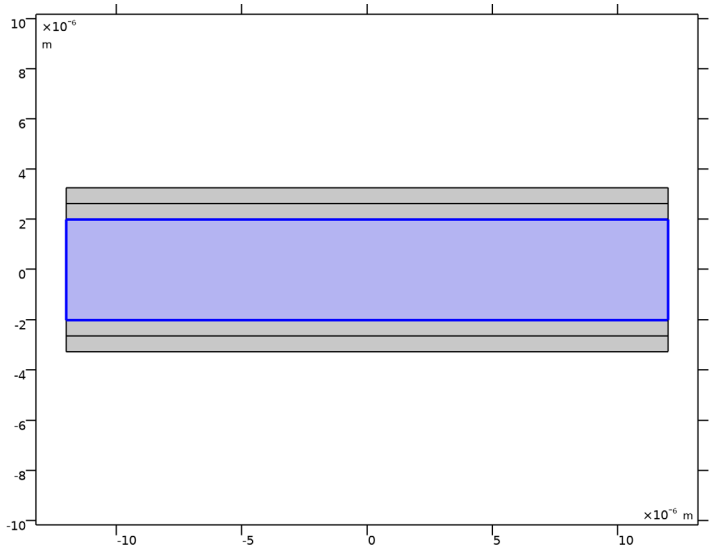
Add some selections that will be used when defining the physics, materials, mesh, and plots.

Liquid Crystal

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Liquid Crystal` in the **Label** text field.

3 Select Domain 3 only. So, the liquid crystal will only occupy the middle layer.

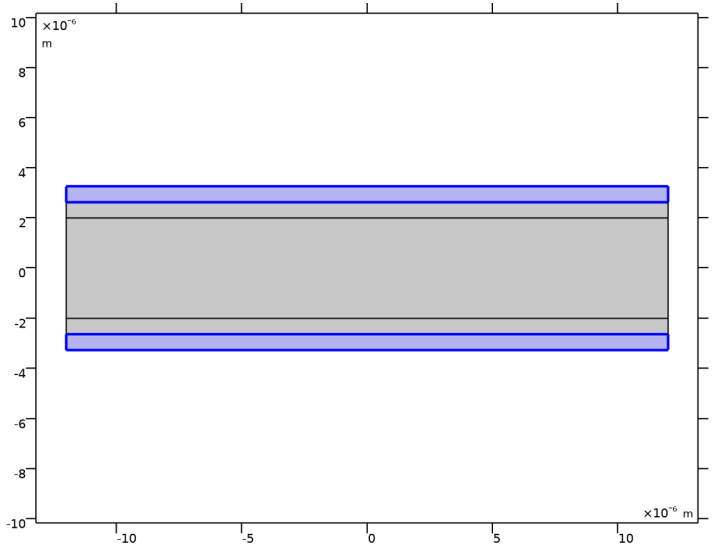


PML

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type PML in the **Label** text field.

3 Select Domains 1 and 5 only. These layers will be used by the Perfectly Matched Layers.



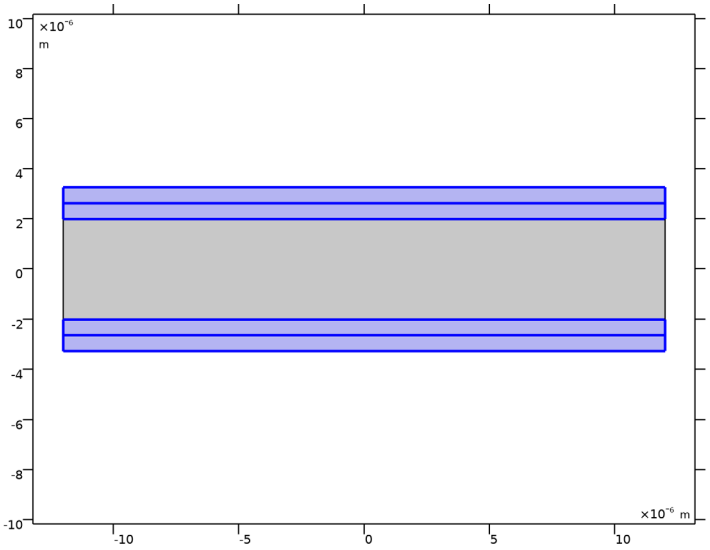
Glass

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Glass` in the **Label** text field.

3 Select Domains 1, 2, 4, and 5 only.

The electromagnetic wave will propagate both in the liquid crystal and in the surrounding glass layers.



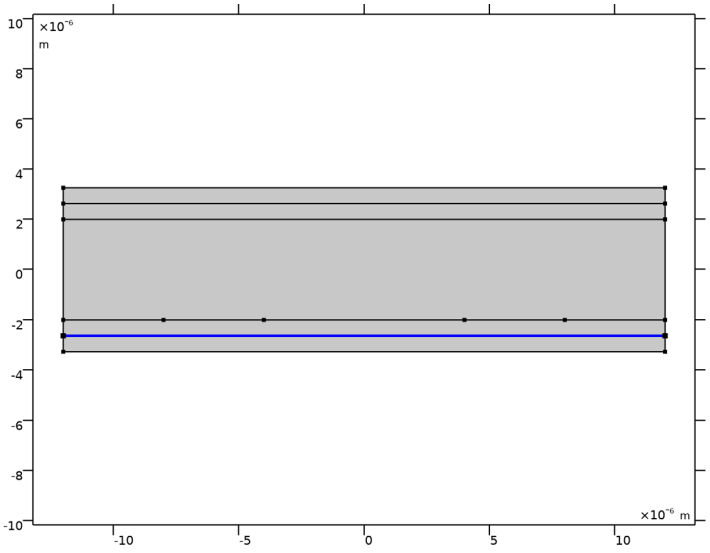
Input Port

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Input Port` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 4 only.



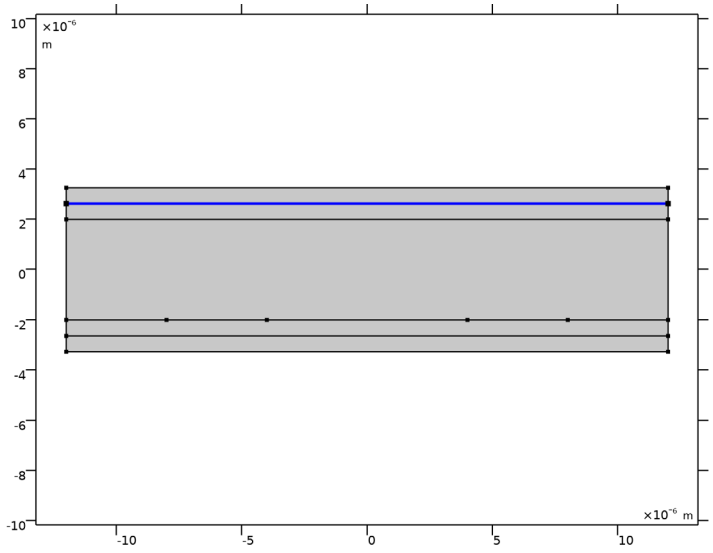
Output Port

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Output Port` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 10 only.



Left Periodic Boundary

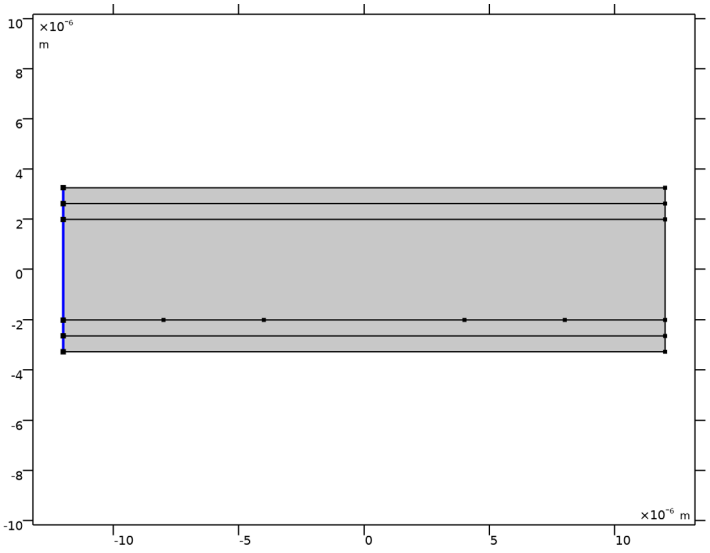
1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Left Periodic Boundary` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

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

5 Select Boundaries 1, 3, 5, 7, and 9 only.



Right Periodic Boundary

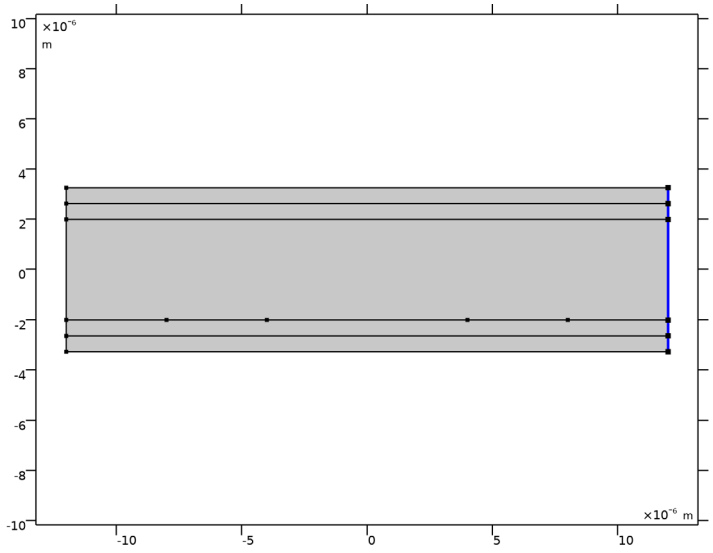
1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Right Periodic Boundary` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

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

5 Select Boundaries 16–20 only.



Periodic Boundaries

1 In the **Definitions** toolbar, click **Union**.

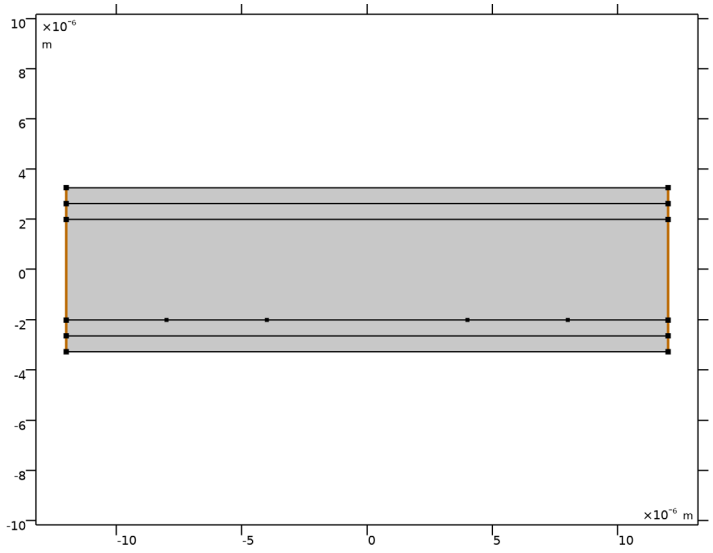
2 In the **Settings** window for **Union**, type `Periodic Boundaries` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Under **Selections to add**, click **Add**.

5 In the **Add** dialog box, in the **Selections to add** list, choose **Left Periodic Boundary** and **Right Periodic Boundary**.

6 Click **OK**.



PML Boundaries

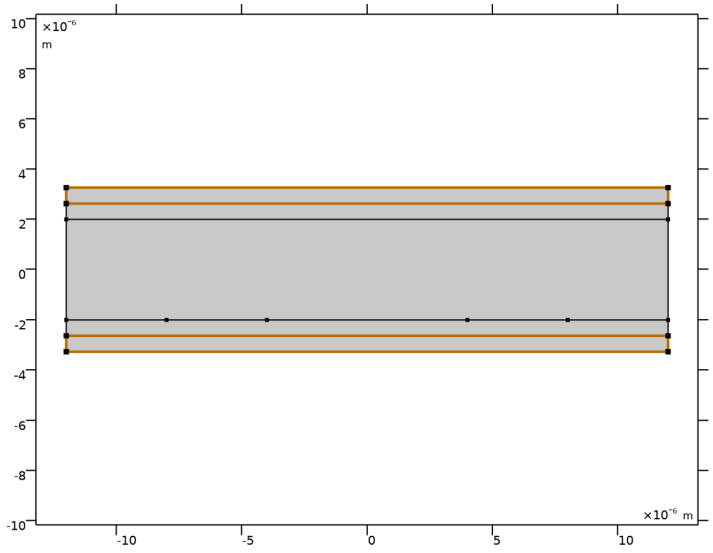
1 In the **Definitions** toolbar, click **Adjacent**.

2 In the **Settings** window for **Adjacent**, type `PML Boundaries` in the **Label** text field.

3 Locate the **Input Entities** section. Under **Input selections**, click **Add**.

4 In the **Add** dialog box, select **PML** in the **Input selections** list.

5 Click **OK**.



PML Distribution Boundaries

1 In the **Definitions** toolbar, click **Intersection**.

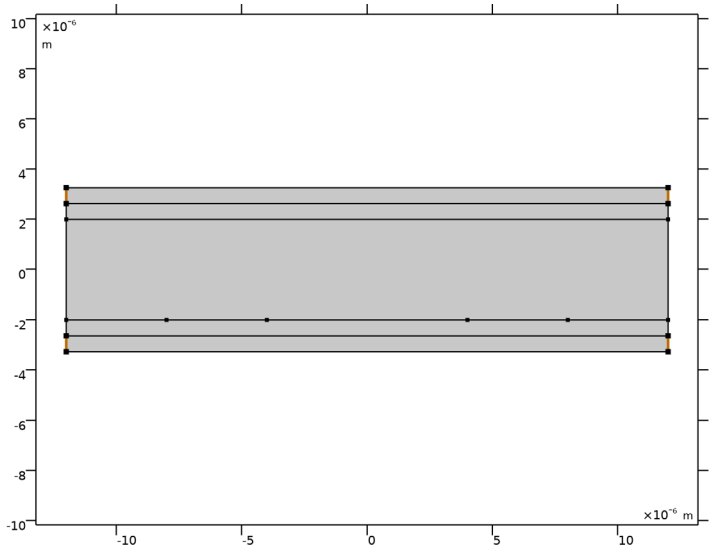
2 In the **Settings** window for **Intersection**, type `PML Distribution Boundaries` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Under **Selections to intersect**, click **Add**.

5 In the **Add** dialog box, in the **Selections to intersect** list, choose **Periodic Boundaries** and **PML Boundaries**.

6 Click **OK**.



Non-PML

1 In the **Definitions** toolbar, click **Difference**.

2 In the **Settings** window for **Difference**, type `Non-PML` in the **Label** text field.

3 Locate the **Input Entities** section. Under **Selections to add**, click **Add**.

4 In the **Add** dialog box, in the **Selections to add** list, choose **Liquid Crystal** and **Glass**.

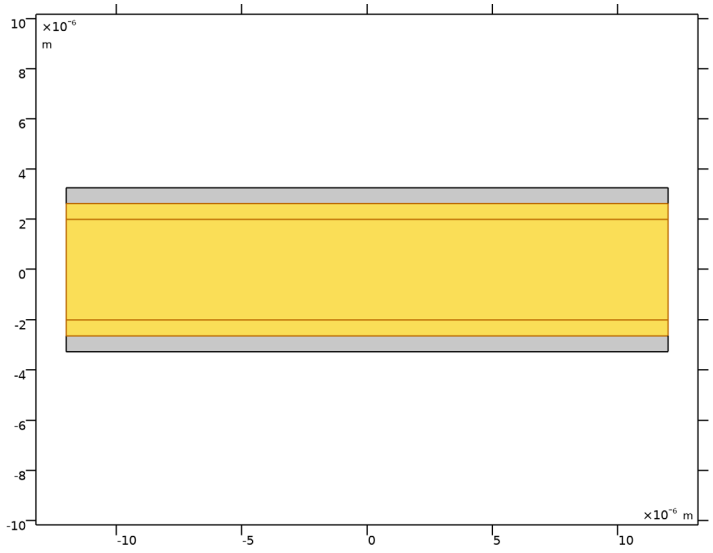
5 Click **OK**.

6 In the **Settings** window for **Difference**, locate the **Input Entities** section.

7 Under **Selections to subtract**, click **Add**.

8 In the **Add** dialog box, select **PML** in the **Selections to subtract** list.

9 Click **OK**.



Electrodes

1 In the **Definitions** toolbar, click **Union**.

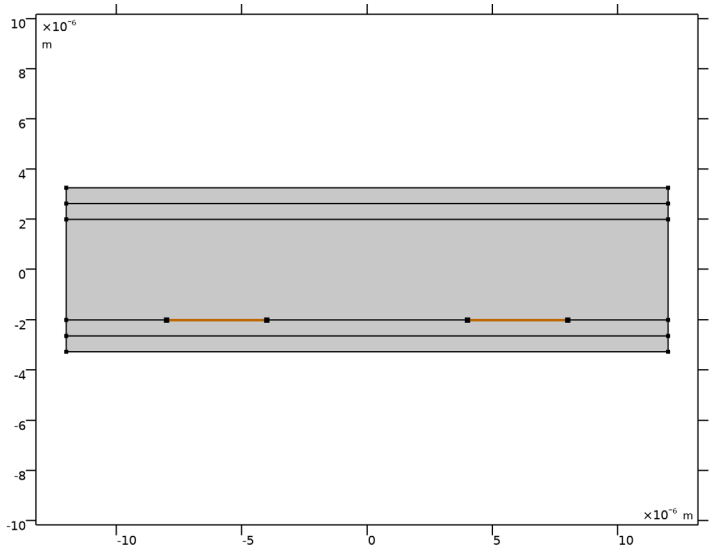
2 In the **Settings** window for **Union**, type `Electrodes` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Under **Selections to add**, click **Add**.

5 In the **Add** dialog box, in the **Selections to add** list, choose **Electric Potential** and **Ground**.

6 Click **OK**.



Liquid Crystal Domain Variables

Before adding the Oseen–Frank equations to the Weak Form PDE interface, add variables representing the elastic free energy density of the liquid crystal material.

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

2 In the **Settings** window for **Variables**, type `Liquid Crystal Domain Variables` 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 **Liquid Crystal**.

5 Locate the **Variables** section. Click **Load from File**.

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

Some of the expressions added above are colored orange, to warn that all variables included are not yet defined. These variables will be defined in a later step.

OSEEN-FRANK

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Weak Form PDE (w)**.

2 In the **Settings** window for **Weak Form PDE**, type `Oseen-Frank` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Liquid Crystal**.

The dependent variables will be two angles that defines the directions for the liquid crystal director field.

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

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

6 Click **Filter**.

7 In the tree, select **General>Plane angle (rad)**.

8 Click **OK**.

9 In the **Settings** window for **Weak Form PDE**, click to expand the **Dependent Variables** section.

10 In the **Number of dependent variables** text field, type `2`.

11 In the **Dependent variables (rad)** table, enter the following settings:

`theta`
`phi`

Weak Form PDE 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Oseen-Frank (w)** click **Weak Form PDE 1**.

2 In the **Settings** window for **Weak Form PDE**, locate the **Weak Expressions** section.

3 In the weak text-field array, type `test(F)` on the first row.

4 In the weak text-field array, type `-var(es.W,theta,phi)` on the second row.

These two weak expressions are added and results in a minimization of the Oseen–Frank free energy with respect to the two angles, the dependent variables `theta` and `phi`.

Strong Anchoring

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

At the top and bottom boundaries, the director angles are fixed. This is called a Strong anchoring condition.

2 In the **Settings** window for **Dirichlet Boundary Condition**, type `Strong Anchoring` in the **Label** text field.

3 Select Boundaries 6, 8, and 12–15 only.

4 Locate the **Dirichlet Boundary Condition** section. In the r_1 text field, type `theta_anchoring`.

5 In the r_2 text field, type `phi_anchoring`.

Periodic Condition 1

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

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

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

ELECTROSTATICS (ES)

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

2 In the **Settings** window for **Electrostatics**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Liquid Crystal**.

Charge Conservation 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Electrostatics (es)** click **Charge Conservation 1**.

2 In the **Settings** window for **Charge Conservation**, locate the **Constitutive Relation D-E** section.

3 From the ε_r list, choose **User defined**. From the list, choose **Symmetric**.

4 In the ε_r table, enter the following settings:

`eps_ortho*(1-nx*nx)+ eps_parallel*nx*nx`	`eps_ortho*(-nx*ny)+ eps_parallel*nx*ny`	`eps_ortho*(-nx*nz)+ eps_parallel*nx*nz`
eps_ortho*(-nx*ny)+ eps_parallel*nx*ny	`eps_ortho*(1-ny*ny)+ eps_parallel*ny*ny`	`eps_ortho*(-ny*nz)+ eps_parallel*ny*nz`
eps_ortho*(-nx*nz)+ eps_parallel*nx*nz	eps_ortho*(-ny*nz)+ eps_parallel*ny*nz	`eps_ortho*(1-nz*nz)+ eps_parallel*nz*nz`

This relative permittivity will be used when solving the electrostatics problem.

Ground 1

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

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

3 From the **Selection** list, choose **Ground**.

Electric Potential 1

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

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

3 From the **Selection** list, choose **Electric Potential**.

4 Locate the **Electric Potential** section. In the V_0 text field, type `V0`.

Periodic Condition 1

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

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

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

DEFINITIONS

Perfectly Matched Layer 1 (pml1)

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

2 In the **Settings** window for **Perfectly Matched Layer**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **PML**.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Wave Equation, Electric 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)** click **Wave Equation, Electric 1**.

2 In the **Settings** window for **Wave Equation, Electric**, locate the **Electric Displacement Field** section.

3 From the **Electric displacement field model** list, choose **Relative permittivity**.

Now, the materials will request values for the relative permittivity, the relative permeability, and the electric conductivity.

MATERIALS

Liquid Crystal

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 `Liquid Crystal` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Liquid Crystal**.

4 Locate the **Material Contents** section. In the table, click to select the cell at row number 1 and column number 4.

5 Right-click the **Relative permittivity** row and choose **Edit**.

6 In the **Relative permittivity** dialog box, choose **Symmetric** from the list.

7 In the table, enter the following settings:

`eps_o*(1-nx*nx)+eps_e*nx*nx`	`eps_o*(-nx*ny)+eps_e*nx*ny`	`eps_o*(-nx*nz)+eps_e*nx*nz`
eps_o*(-nx*ny)+eps_e*nx*ny	`eps_o*(1-ny*ny)+eps_e*ny*ny`	`eps_o*(-ny*nz)+eps_e*ny*nz`
eps_o*(-nx*nz)+eps_e*nx*nz	eps_o*(-ny*nz)+eps_e*ny*nz	`eps_o*(1-nz*nz)+eps_e*nz*nz`

8 Click **OK**.

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

10 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	I	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

The material properties above will only be used by the **Electromagnetic Waves, Frequency Domain** interface. The relative permittivity for the **Electrostatics** interface has already been added to the **Charge Conservation** node as a user-defined material property.

Glass

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

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

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

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

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	n_e	1	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

Using the extraordinary refractive index will reduce reflections at the boundaries between the liquid crystal and the glass.

DEFINITIONS

Port Mode Field Polarization Variables

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

2 In the **Settings** window for **Variables**, type `Port Mode Field Polarization Variables` 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 **Glass**.

5 Locate the **Variables** section. Click **Load from File**.

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

Defining the liquid crystal anchoring directions also in the glass layers, facilitates the definition of the port mode polarizations.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Port 1

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

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

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

4 Locate the **Port Properties** section. From the **Type of port** list, choose **Periodic**.

5 Select the **Activate slit condition on interior port** check box.

6 From the **Slit type** list, choose **Domain-backed**.

7 Locate the **Port Mode Settings** section. Specify the $\mathbf{E}_0$ vector as

nx	x
nz	z

Orthogonal Polarization 1

In the **Physics** toolbar, click **Attributes** and choose **Orthogonal Polarization**.

Port 1

In the **Model Builder** window, right-click **Port 1** and choose **Duplicate**.

Port 2

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

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

3 From the **Selection** list, choose **Output Port**.

4 Locate the **Port Properties** section. From the **Wave excitation at this port** list, choose **Off**.

5 Click **Toggle Power Flow Direction**.

Periodic Condition 1

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

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

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

MESH 1

Since the relative permittivity is inhomogeneous and anisotropic, physics-controlled meshing cannot be used. Instead, the mesh will be built manually.

Distribution 1

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

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

3 From the **Selection** list, choose **PML Distribution Boundaries**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type 10.

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 `lda0/n_e/6`, to make sure that the electromagnetic wave is properly resolved.

Identical Mesh 1

1 In the **Mesh** toolbar, click **More Attributes** and choose **Identical Mesh**.

2 In the **Settings** window for **Identical Mesh**, locate the **First Entity Group** section.

3 From the **Selection** list, choose **Left Periodic Boundary**.

4 Locate the **Second Entity Group** section. From the **Selection** list, choose **Right Periodic Boundary**.

The **Identical Mesh** feature makes the edge meshes on the two opposing periodic boundaries identical.

Free Triangular 1

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

2 In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Non-PML**.

Mapped 1

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

2 In the **Settings** window for **Mapped**, click **Build All**.

STUDY 1

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
V0 (Applied potential)		V

5 Click **Range**.

6 In the **Range** dialog box, type `0[V]` in the **Start** text field.

7 In the **Step** text field, type `0.5[V]`.

8 In the **Stop** text field, type `5[V]`.

9 Click **Add**.

10 In the **Settings** window for **Parametric Sweep**, click to expand the **Advanced Settings** section.

11 Select the **Reuse solution from previous step** check box, to reduce the number of nonlinear iterations.

Step 2: Wavelength Domain

1 In the **Study** toolbar, click **Study Steps** and choose **Frequency Domain> Wavelength Domain**.

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

3 In the **Wavelengths** text field, type `lda0`.

4 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check boxes for **Oseen-Frank (w)** and **Electrostatics (es)**.

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

RESULTS

We will not be interested in plotting any result from the PML domains, so those domains can be removed from the dataset.

Study 1/Parametric Solutions 1 (sol3)

In the **Model Builder** window, expand the **Results>Datasets** node, then click **Study 1/ Parametric Solutions 1 (sol3)**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

2 In the **Settings** window for **Selection**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Non-PML**.

Oseen-Frank

1 In the **Model Builder** window, under **Results** click **Oseen-Frank**.

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 Click to expand the **Plot Array** section. Select the **Enable** check box.

5 From the **Array axis** list, choose **y**.

The last settings will make it possible to plot multiple plots in the same **Graphics** window.

Surface 1

1 In the **Model Builder** window, expand the **Oseen-Frank** node, then click **Surface 1**.

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

3 From the **Unit** list, choose **°**.

4 Locate the **Coloring and Style** section. Click  **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>Dipole** in the tree.

6 Click **OK**.

7 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

8 From the **Scale** list, choose **Linear symmetric**.

9 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 `phi`.

4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Arrow Surface 1

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

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

3 In the **x-component** text field, type `nx`.

4 In the **y-component** text field, type `ny`.

5 Locate the **Arrow Positioning** section. Find the **x grid points** subsection. In the **Points** text field, type `25`.

Oseen-Frank

Add **Line** plots to indicate the positions of the electrodes.

Line 1

1 Right-click **Oseen-Frank** and choose **Line**.

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

3 In the **Expression** text field, type `1`.

4 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

5 In the **Tube radius expression** text field, type 2.

6 From the **Coloring** list, choose **Uniform**.

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

8 Click to expand the **Plot Array** section. Select the **Manual indexing** check box.

Selection 1

1 Right-click **Line 1** and choose **Selection**.

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

3 From the **Selection** list, choose **Electrodes**.

Line 1

In the **Model Builder** window, right-click **Line 1** and choose **Duplicate**.

Line 2

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

2 In the **Settings** window for **Line**, locate the **Plot Array** section.

3 In the **Index** text field, type 1.

4 Right-click **Line 2** and choose **Duplicate**.

Line 3

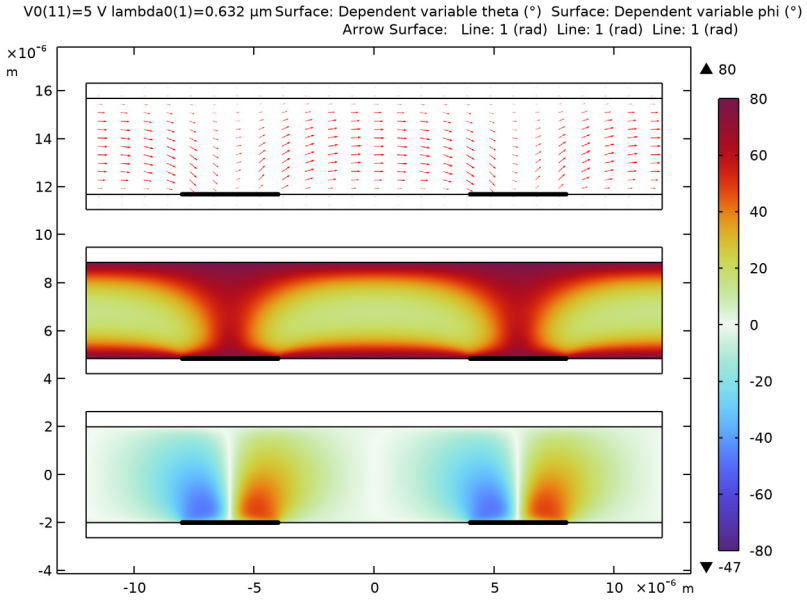
1 In the **Model Builder** window, click **Line 3**.

2 In the **Settings** window for **Line**, locate the **Plot Array** section.

3 In the **Index** text field, type 2.

4 In the **Oseen-Frank** toolbar, click  **Plot**.

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



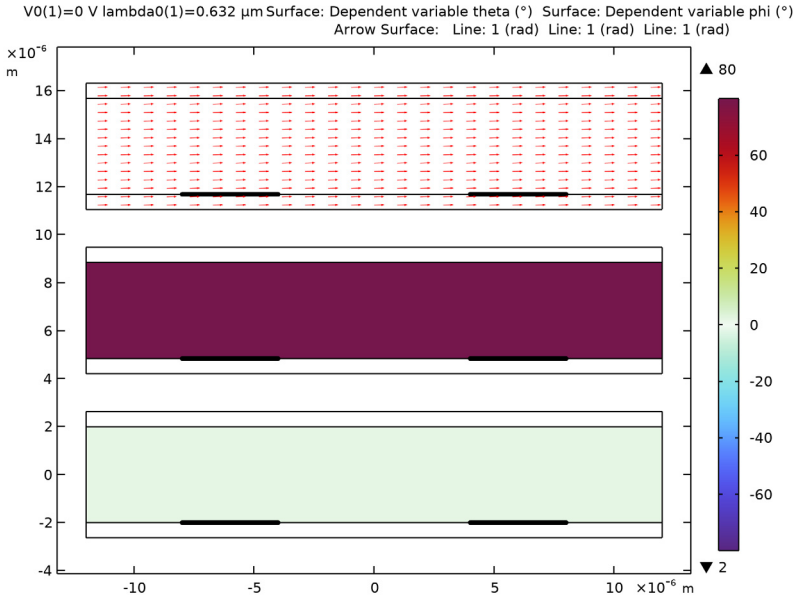
Notice that the angles `theta` and `phi` are anchored to 2 and 80 degrees, respectively, at both the top and bottom boundaries.

Furthermore, between the two electrodes, the angle `phi` as at its minimum value and the angle `theta` is zero. So, the directors are almost aligned with the electric field in this region.

Oseen-Frank

1 In the **Model Builder** window, click **Oseen-Frank**.

2 In the **Settings** window for **2D Plot Group**, click **Plot First**.



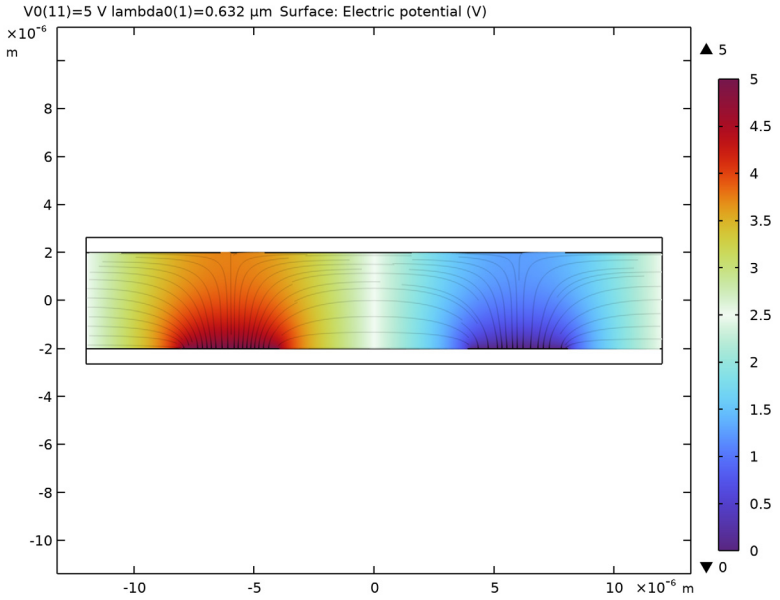
With no applied electric field, the directors are pointing in the anchoring direction.

Electric Potential (es)

1 In the **Model Builder** window, click **Electric Potential (es)**.

2 In the **Electric Potential (es)** toolbar, click **Plot**.

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



As expected, the electric field is almost parallel to the electrodes in the region between the electrodes. Thereby, the liquid crystal directors will align in the *x* direction at the larger applied voltages.

Electric Field (ewfd)

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

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

3 Select the **x-axis label** check box. In the associated text field, type `x`.

4 Select the **y-axis label** check box. In the associated text field, type `y`.

5 Locate the **Plot Array** section. Select the **Enable** check box.

6 From the **Array axis** list, choose **y**.

With the settings above, plots of different electric field components can be presented in the same **Graphics** window.

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 `nx*ewfd.Ex+nz*ewfd.Ez`. This expression corresponds to the input field polarization.

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Wave>WaveLight** in the tree.

6 Click **OK**.

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

Surface 2

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

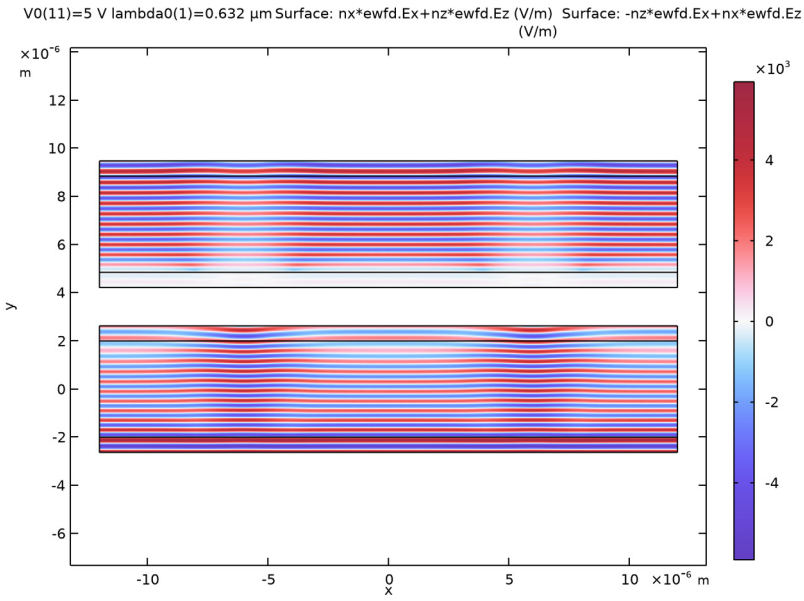
2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `-nz*ewfd.Ex+nx*ewfd.Ez`. This expression corresponds to a polarization orthogonal to the input field.

4 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

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

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

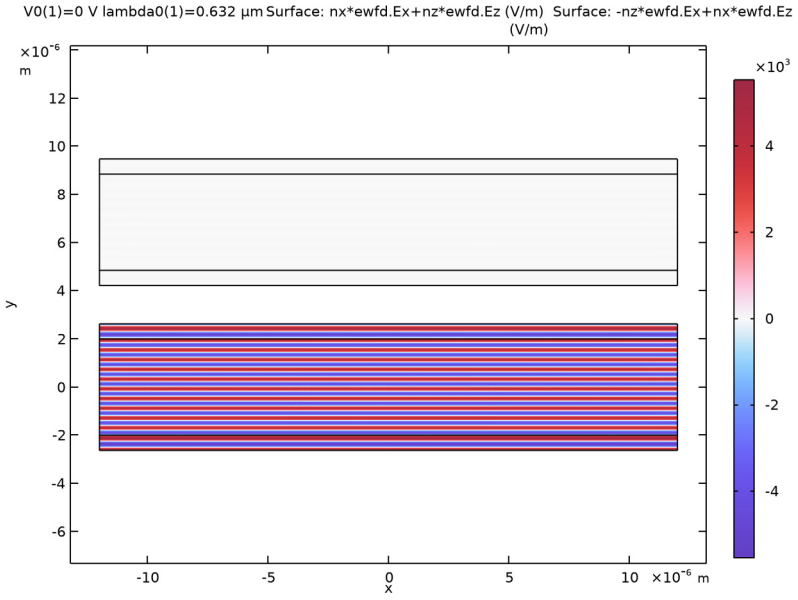


Notice that the field with a polarization orthogonal to the input field (the top plot) is generated as the wave propagates in the *y*-direction. Furthermore, diffraction effects

happen above the electrodes, where the liquid crystal directors mostly align in the *y* direction.

As the analyzer is set to let the orthogonal polarization through, the pixel will appear bright at this applied voltage.

7 Click **Plot First**.



Now, the orthogonal polarization is almost zero. So, at zero applied voltage the pixel will appear black.

Transmittance (ewfd)

The reflectance will be very small, so it is more important to display the transmittances for the different modes.

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

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

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Transmittance (1)`.

Global 1

1 In the **Model Builder** window, expand the **Transmittance (ewfd)** node, then click **Global 1**.

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

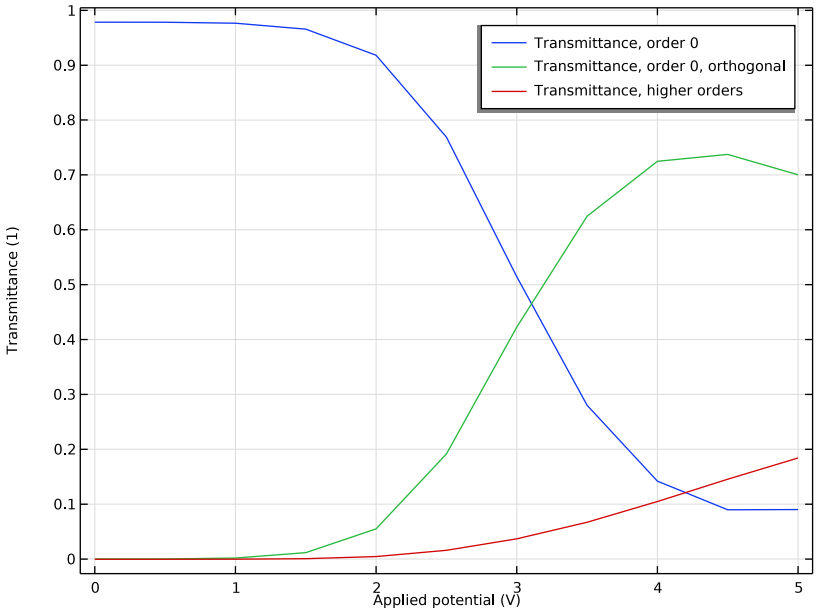
3 Ctrl-click to select table rows 1–3 and 6–8.

4 Click **Delete**.

5 In the **Expression** text field, type `1-ewfd.RTtotal`.

6 In the **Description** text field, type `Transmittance, higher orders`.

7 In the **Transmittance (ewfd)** toolbar, click **Plot**.



Notice that the orthogonal polarization (that will pass through the analyzer) is almost zero at zero applied voltage and larger than 70% at 4.5 V. Thus, this cell will have a large dynamic range.

The red curve indicates that diffraction to higher orders, propagating in nonnormal directions, occurs as the applied voltage is increased.

Polarization Plot (ewfd)

1 In the **Model Builder** window, under **Results** click **Polarization Plot (ewfd)**.

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

3 In the **Parameter values (V0 (V))** list, choose **0** and **4.5**.

Polarization 1

1 In the **Model Builder** window, expand the **Polarization Plot (ewfd)** node.

2 Right-click **Polarization 1** and choose **Delete**.

Polarization 2

1 In the **Model Builder** window, under **Results>Polarization Plot (ewfd)** click **Polarization 2**.

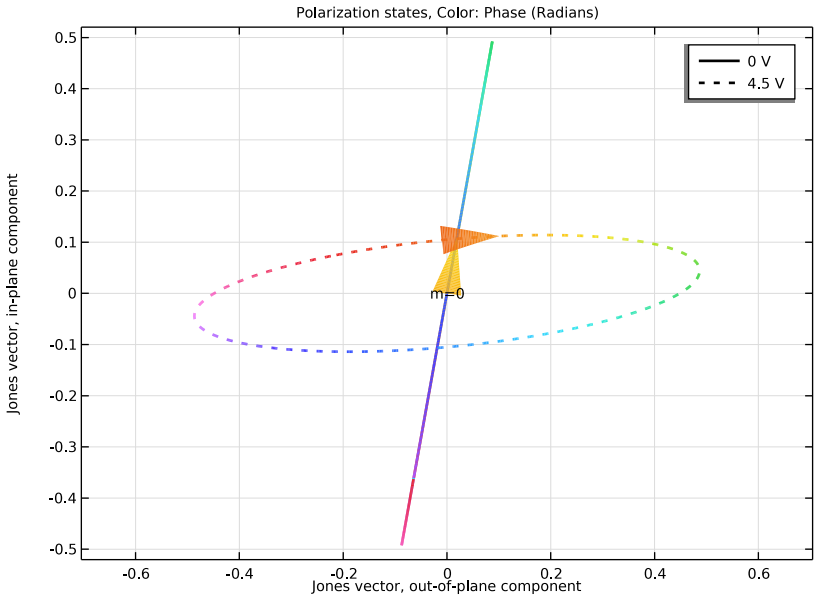
2 In the **Settings** window for **Polarization**, click to expand the **Coloring and Style** section.

3 Find the **Line style** subsection. From the **Line** list, choose **Cycle**.

4 Click to expand the **Legends** section. In the table, enter the following settings:

Legends
0 V
4.5 V

5 In the **Polarization Plot (ewfd)** toolbar, click **Plot**.



The polarization plot shows that the field is linearly polarized at zero applied voltage and elliptically polarized at 4.5 V.

Study 1/Parametric Solutions 1 (sol3)

Finally, make a 3D plot displaying the director orientations and the applied electric field.

In the **Model Builder** window, under **Results>Datasets** right-click **Study 1/ Parametric Solutions 1 (sol3)** and choose **Duplicate**.

Selection

1 In the **Model Builder** window, expand the **Study 1/Parametric Solutions 1 (4) (sol3)** node, then click **Selection**.

2 In the **Settings** window for **Selection**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Liquid Crystal**.

Extrusion 2D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Extrusion 2D**.

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

3 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (4) (sol3)**.

4 Locate the **Extrusion** section. In the **z maximum** text field, type `t_LC`.

Directors and Applied Field

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `Directors and Applied Field` in the **Label** text field.

Arrow Volume 1

1 Right-click **Directors and Applied Field** and choose **Arrow Volume**.

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

3 In the **x-component** text field, type `nx`.

4 In the **y-component** text field, type `ny`.

5 In the **z-component** text field, type `nz`.

6 Locate the **Arrow Positioning** section. Find the **x grid points** subsection. In the **Points** text field, type `11`.

7 Find the **y grid points** subsection. In the **Points** text field, type `9`.

8 Find the **z grid points** subsection. In the **Points** text field, type `1`.

9 Locate the **Coloring and Style** section. From the **Color** list, choose **Custom**.

10 On Windows, click the colored bar underneath, or — if you are running the cross-platform desktop — the **Color** button.

11 Click **Define custom colors**.

12 Set the RGB values to 105, 105, and 105, respectively.

13 Click **Add to custom colors**.

14 Click **Show color palette only** or **OK** on the cross-platform desktop.

Slice 1

1 In the **Model Builder** window, right-click **Directors and Applied Field** and choose **Slice**.

2 In the **Settings** window for **Slice**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electrostatics> Electric>V - Electric potential - V**.

3 Locate the **Plane Data** section. From the **Plane** list, choose **xy-planes**.

4 In the **Planes** text field, type 1.

5 Locate the **Coloring and Style** section. Click  **Change Color Table**.

6 In the **Color Table** dialog box, select **Rainbow>Dipole** in the tree.

7 Click **OK**.

Directors and Applied Field

1 In the **Model Builder** window, click **Directors and Applied Field**.

2 In the **Settings** window for **3D Plot Group**, locate the **Plot Settings** section.

3 Clear the **Plot dataset edges** check box.

4 Click the  **Show Grid** button in the **Graphics** toolbar.

Streamline 1

1 Right-click **Directors and Applied Field** and choose **Streamline**.

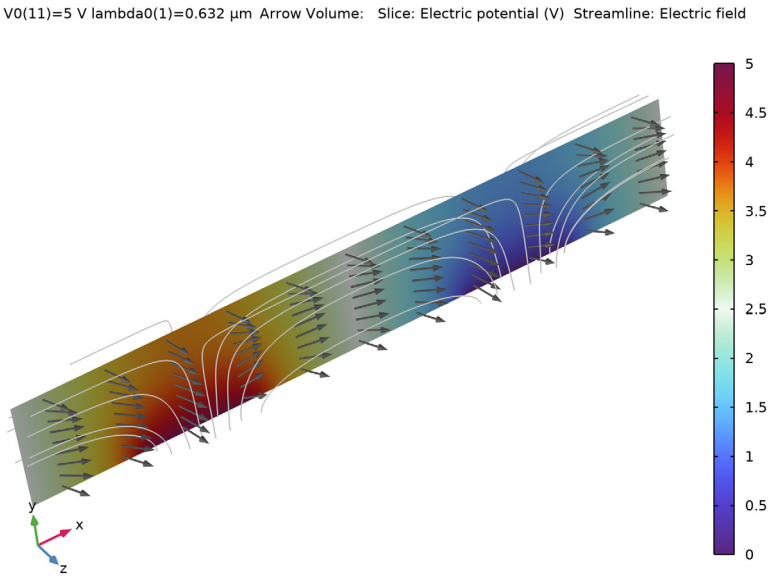
2 In the **Settings** window for **Streamline**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electrostatics> Electric>es.Ex,es.Ey,es.Ez - Electric field**.

3 Locate the **Streamline Positioning** section. From the **Positioning** list, choose **Uniform density**.

4 Locate the **Coloring and Style** section. Find the **Point style** subsection. From the **Color** list, choose **Gray**.

5 Use the mouse to orient the plot.

6 In the **Directors and Applied Field** toolbar, click **Plot**.



This plot shows that the liquid crystal directors rotate and almost align with the electric field in the region between the electrodes.