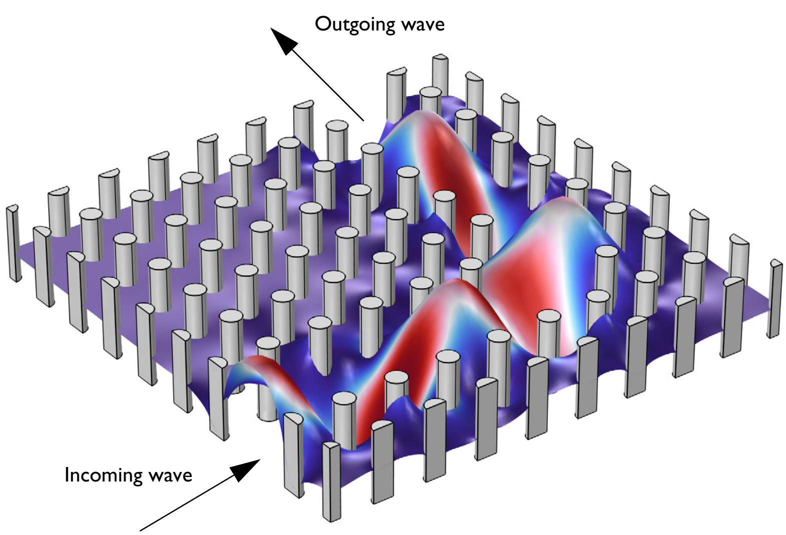
Photonic Crystal

Photonic crystal devices are periodic structures of alternating layers of materials with different refractive indices. Waveguides that are confined inside of a photonic crystal can have very sharp low-loss bends, which may enable an increase in integration density of several orders of magnitude.

Introduction

This application describes the wave propagation in a photonic crystal that consists of GaAs pillars placed equidistant from each other. The distance between the pillars prevents light of certain wavelengths to propagate into the crystal structure. Depending on the distance between the pillars, waves within a specific frequency range are reflected instead of propagating through the crystal. This frequency range is called the photonic band gap (Ref. 1). By removing some of the GaAs pillars in the crystal structure you can create a guide for the frequencies within the band gap. Light can then propagate along the outlined guide geometry.



Model Definition

The geometry is a square of air with an array of circular pillars of GaAs as described above. Some pillars are removed to make a waveguide with a 90° bend.

The objective of the application is to study TE waves propagating through the crystal. To model these, use a scalar equation for the transverse electric field component E_z,

$$-\nabla \cdot \nabla E_z - n^2 k_0^2 E_z = 0$$

where n is the refractive index and k_0 is the free-space wave number.

Because there are no physical boundaries, you can use the scattering boundary condition at all boundaries. Set the amplitude E_z to 1 on the boundary of the incoming wave.

Results and Discussion

Figure 1 contains a plot of the z-component of the electric field. It clearly shows the propagation of the wave through the guide.

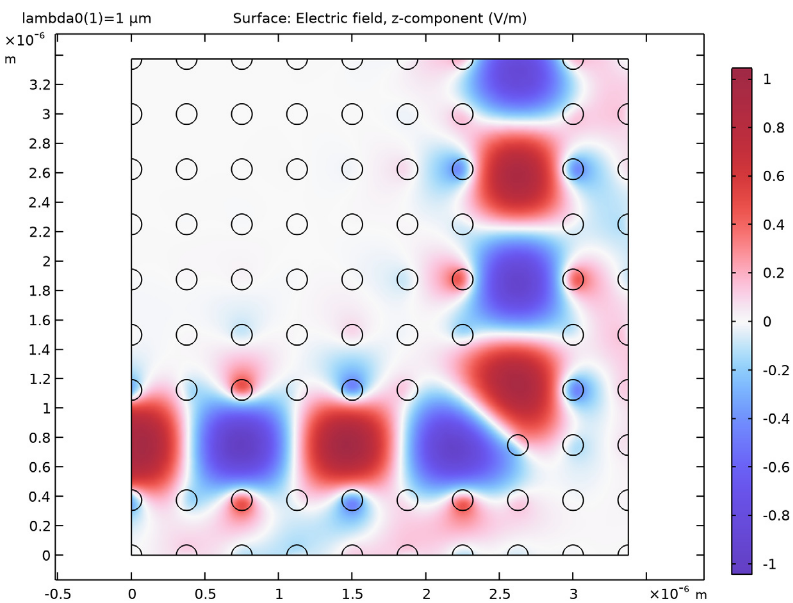


Figure 1: The z-component of the electric field showing how the wave propagates along the path defined by the pillars.

If the angular frequency of the incoming wave is less than the cutoff frequency of the waveguide, the wave does not propagate through the outlined guide geometry. In Figure 2 the wavelength has been increased by a factor of 1.3.

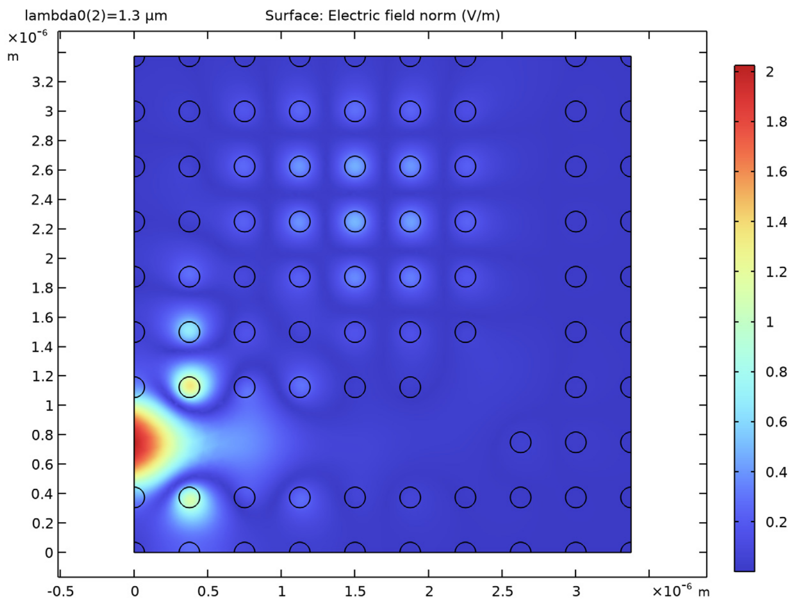


Figure 2: A longer wavelength does not propagate through the guide. This plot shows the norm of the electric field.

Reference

1. J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic Crystals (Modeling the Flow of Light)*, Princeton University Press, 1995.

Application Library path: `Wave_Optics_Module/Couplers_Filters_and_Mirrors/photonic_crystal`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.
2 In the **Select Physics** tree, select **Optics>Wave Optics>Electromagnetic Waves, Frequency Domain (ewfd)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Wavelength Domain**.
6 Click **Done**.

GEOMETRY 1

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.
2 In the **Settings** window for **Import**, locate the **Import** section.
3 Click **Browse**.
4 Browse to the model's Application Libraries folder and double-click the file `photonic_crystal.mphbin`.
5 Click **Import**.
6 Click the **Zoom Extents** button in the **Graphics** toolbar.

MATERIALS

The refractive index of GaAs depends on the frequency. The material is added from the Optical Material Library.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.
2 Go to the **Add Material** window.
3 In the tree, select **Optical>Inorganic Materials>As - Arsenides>Experimental data>GaAs (Gallium arsenide) (Skauli et al. 2003: n 0.97-17 um)**.
4 Click **Add to Component** in the window toolbar.
5 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

GaAs (Gallium arsenide) (Skauli et al. 2003: n 0.97-17 um) (mat1)

Select Domains 1 and 3–86 only. This is most easily done by removing Domain 2 from the list once you have selected all domains.

Air

1 In the **Model Builder** window, right-click **Materials** and choose **Blank Material**.

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

3 Select Domain 2 only.

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

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

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

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

2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.

3 From the **Electric field components solved for** list, choose **Out-of-plane vector**, as only the out-of-plane component will be solved for.

Scattering Boundary Condition 1

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

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

3 From the **Selection** list, choose **All boundaries**.

Scattering Boundary Condition 2

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

2 Select Boundary 5 only.

3 In the **Settings** window for **Scattering Boundary Condition**, locate the **Scattering Boundary Condition** section.

4 From the **Incident field** list, choose **Wave given by E field**.

5 Specify the $\mathbf{E}_0$ vector as

0	x
0	y
1	z

STUDY 1

Step 1: Wavelength Domain

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

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

3 In the **Wavelengths** text field, type `1[um] 1.3[um]`.

This will get you one solution for a free space wavelength of 1 µm, and one for a free space wavelength of 1.3 µm.

4 In the **Home** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd)

The default plot shows the distribution of the electric field norm for the lowest of the frequencies. Because this is below the cutoff frequency of the waveguide, the wave does not propagate through the outlined guide geometry.

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

2 From the **Parameter value (lambda0 (µm))** list, choose **1**.

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

300 THz, or a free space wavelength of 1 µm, is within the band gap. The wave propagates all the way through the geometry, losing only a little of its energy. Try visualizing the instantaneous value of the field.

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**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Electric>Electric field - V/m>ewfd.Ez - Electric field, z-component**.

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

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

5 Click **OK**.

The WaveLight color table looks better if the range is symmetric around zero.

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

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

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

Cut Line 2D 1

Finally, create a line plot comparing how the electric field magnitude falls off as the waves of the two frequencies under study enter the waveguide.

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

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

3 In row **Point 1**, set **Y** to `0.75e-6`.

4 In row **Point 2**, set **X** to `2.5e-6` and **y** to `0.75e-6`.

5 Click **Plot**.

1D Plot Group 2

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

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

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

Line Graph 1

1 Right-click **1D Plot Group 2** and choose **Line Graph**.

2 In the **1D Plot Group 2** toolbar, click **Plot**.