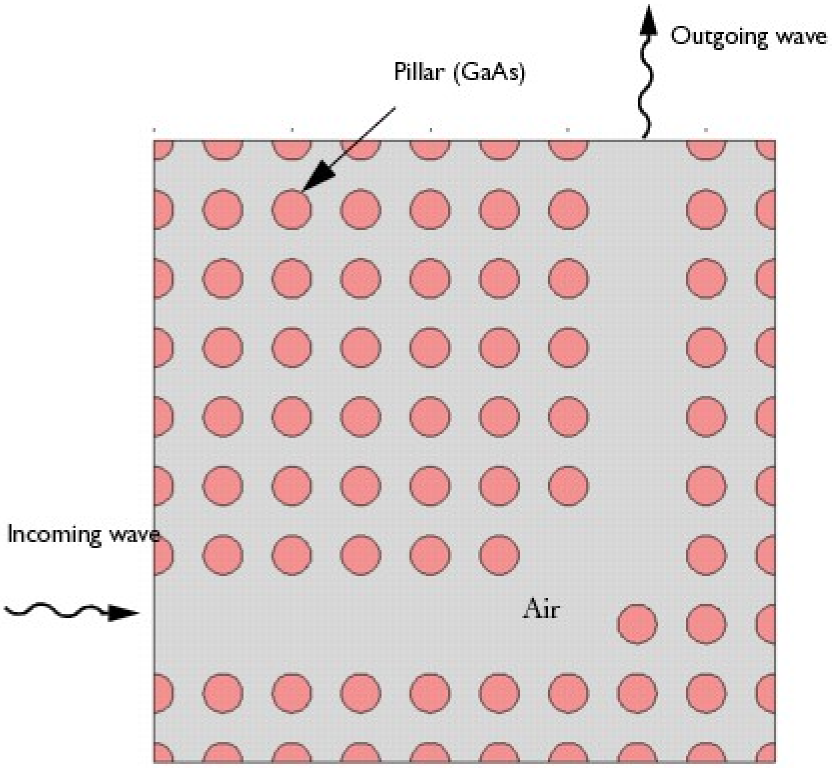
Photonic Crystal

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 model 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 bandgap (Ref. 1). By removing some of the GaAs pillars in the crystal structure you can create a guide for the frequencies within the bandgap. 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 model 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 4-5 contains a plot of the z component of the electric field. It clearly shows the propagation of the wave through the guide.

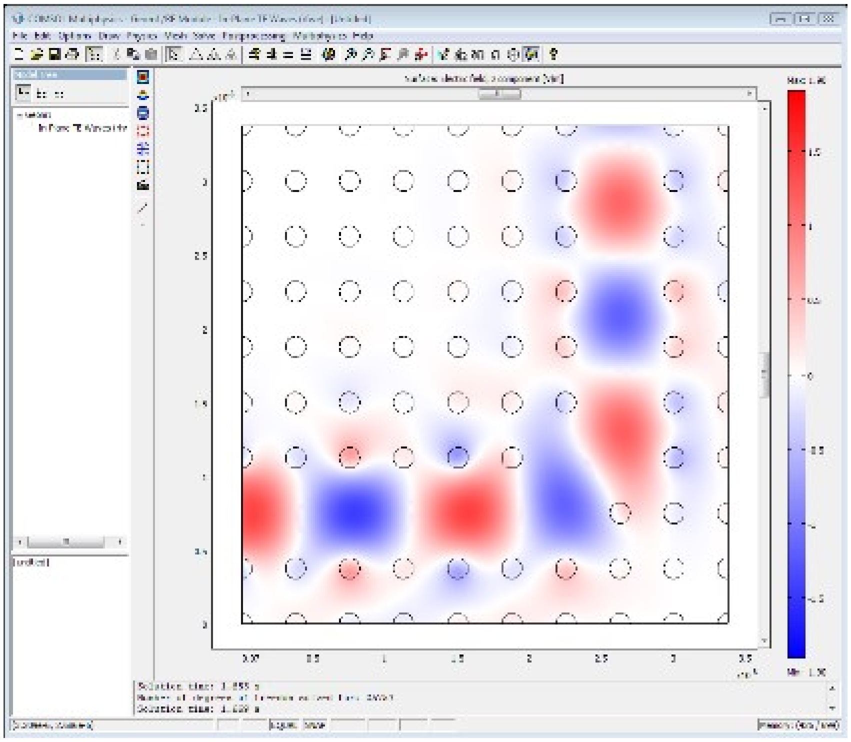
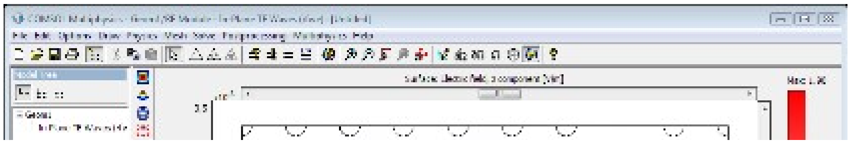


Figure 4-5: The z component of the electric field showing how the wave propagates along the path defined by the pillars.

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 4-6 the wavelength has been increased by a factor of 1.17.



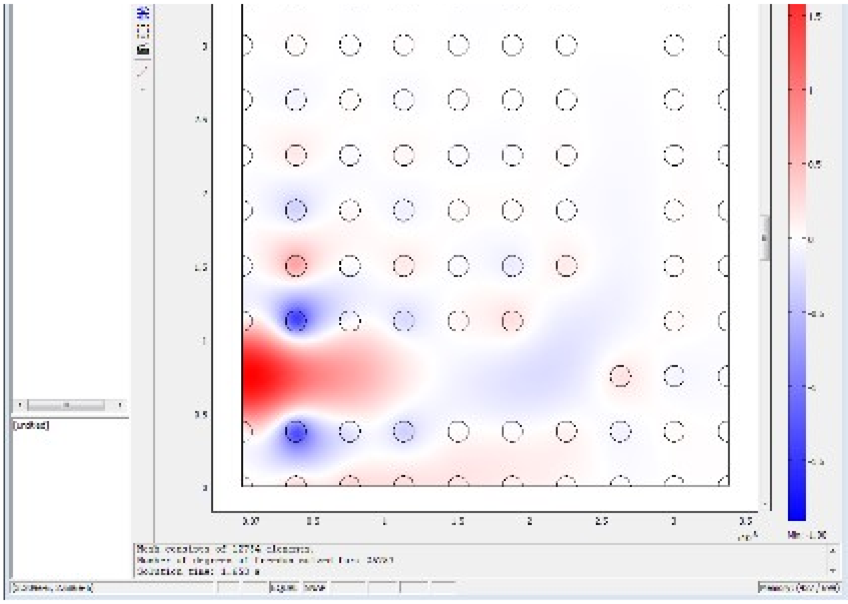


Figure 4-6: A longer wavelength will not propagate through the guide.

References

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

2. Chuang Shun Lien, *Physics of Optoelectronic Devices*, Wiley series in pure and applied optics, 1995.

Model Library path: `RF_Module/Optics_and_Photonics/photonic_crystal`

Modeling Using the Graphical User Interface

MODEL NAVIGATOR

1 Select **2D** from the **Space dimension** list.

2 In the list of application modes, select **RF Module>In-Plane Waves> TE Waves>Harmonic propagation**.

3 Click **OK**.

APPLICATION MODE PROPERTIES

For convenience, specify that the wavelength rather than the frequency should be used as input. In the **Application Mode Properties** dialog box set the property **Specify wave using** to **Free space wavelength**.

OPTIONS AND SETTINGS

1 From the **Options** menu, choose **Axes/Grid Settings**.

2

Set axis and grid settings according to the following table (clear the **Auto** check box to enter the grid settings).

AXIS		**GRID**	
x min	`0`	x spacing	`5e-7`
x max	`5e-6`	Extra x	`7e-8`
y min	`-1e-6`	y spacing	`5e-7`
y max	`4e-6`	Extra y	

3 Click **OK**.

GEOMETRY MODELING

The easiest way to create the crystal geometry is using a array of geometry objects.

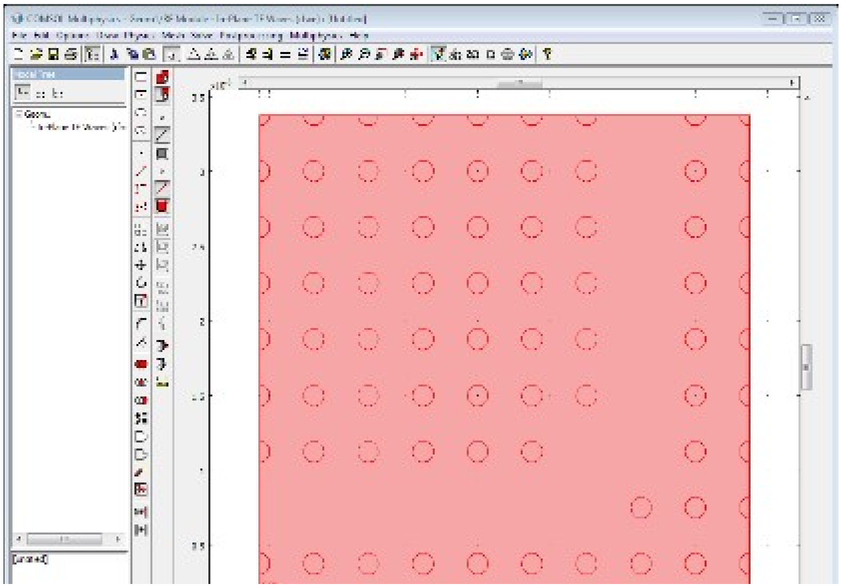
1 Start by drawing a circle with the radius `7e-8` and the center at $x = 0$, $y = 0$.

2 Select the circle and click the **Array** button. In the **Displacement** edit fields, type `3.75e-7` for the displacements in both directions and in the **Array size** edit fields, type `10` in both the x and y directions

3 Create the guide as a 90° bend by removing some pillars from the array. Remove the circles C3, C13, C23, C33, C43, C53, C63, C64, and C74 to C80.

4 Use the **Rectangle** dialog box to create a rectangle intersecting with all pillars. Set both the **Width** and **Height** to `9*3.75e-7`.

5 Select all objects and open the **Create Composite Object** dialog box. Type `R1*(C1+C2+...+C99+C100+R1)` in the **Set formula** edit field and click **OK** to create an object with the regions outside the rectangle removed. The sum within parentheses in the set formula creates a union of all objects. The * operator then takes the intersection of this union and the rectangle.



PHYSICS SETTINGS

Scalar Variables

In the **Application Scalar Variables** dialog box, set the wavelength to `1e-6`.

Boundary Conditions

Use low-reflecting boundary conditions on all exterior boundaries. Apply a source at the input port. These settings are summarized in the following table.

SETTINGS	**BOUNDARY 5**	**ALL OTHERS**
Boundary condition	Scattering boundary condition	Scattering boundary condition
E_{0z}	`1`	`0`
Wave type	Plane wave	Plane wave

Subdomain Settings

Enter subdomain settings according to the following table.

SETTINGS	**SUBDOMAINS 1, 3 –86**	**SUBDOMAIN 2**
n	`n_GaAs`	`n_Air`

Because the refractive index of GaAs is frequency dependent, define the refractive indices in the model using expression variables. The expression defines a linearized frequency dependency of the refractive index of GaAs between the refractive index values corresponding to the wavelengths 1.0332 µm and 1.2339 µm according to Ref. 2. In the **Options>Expressions>Scalar Expressions** dialog box, define the variables `n_Air` and `n_GaAs`. The descriptions are optional. When done, click **OK**.

NAME	**EXPRESSION**	**DESCRIPTION**
`n_Air`	`1`	`Refractive index, air`
`n_GaAs`	`-3.3285e5*lambda0_rfwe[1/m] +3.5031`	`Refractive index, GaAs`

MESH GENERATION

1 Change the default mesh parameters to get an applicable mesh. Open the **Free Mesh Parameters** dialog box, click the **Custom mesh size** button, and set **Element growth rate** to `1.55` and **Mesh curvature factor** to `0.65`.

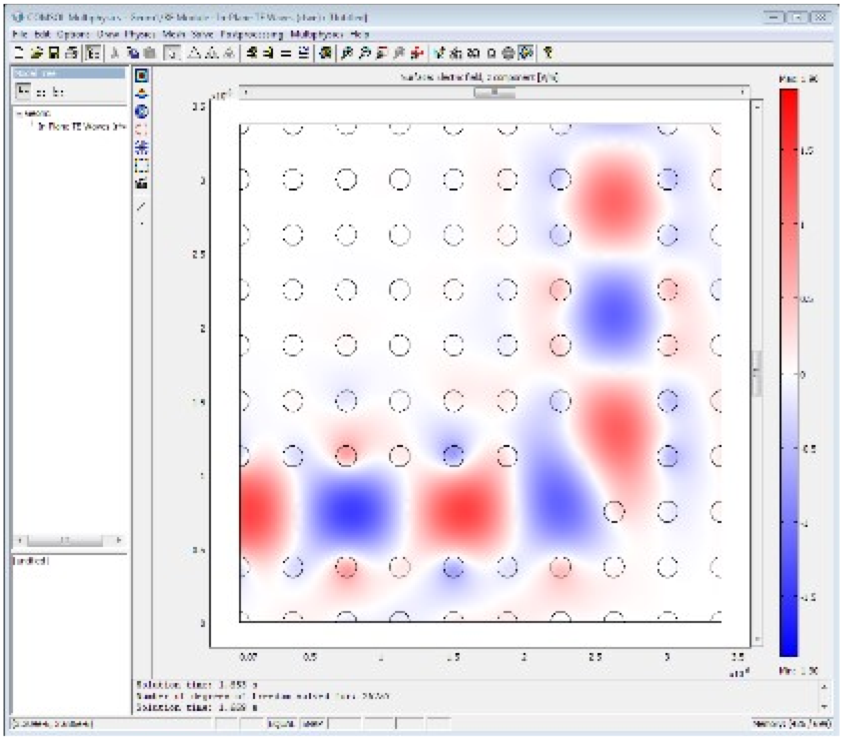
2 Initialize the mesh.

COMPUTING THE SOLUTION

Click the **Solve** button on the Main toolbar to solve the problem with the default solver.

POSTPROCESSING AND VISUALIZATION

By default, the *z* component of the electric field is visualized. This clearly shows the propagation of the wave through the guide. On the **Surface** page in the **Plot Parameters** dialog box, change the **Color table** to **WaveLight**. This makes it easier to identify the wave.



If the angular frequency of the incoming wave is less than the cutoff frequency of the waveguide, the wave will not propagate through the outlined guide geometry.

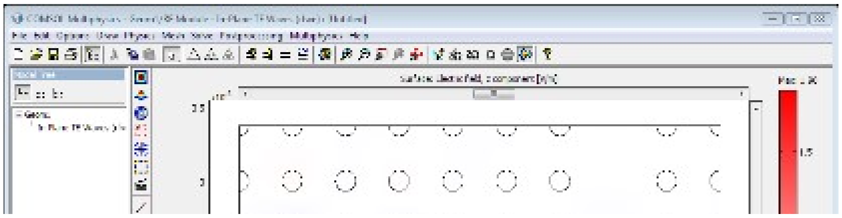
1 Open the **Application Scalar Variables** dialog box and multiply the wavelength by `1.17`.

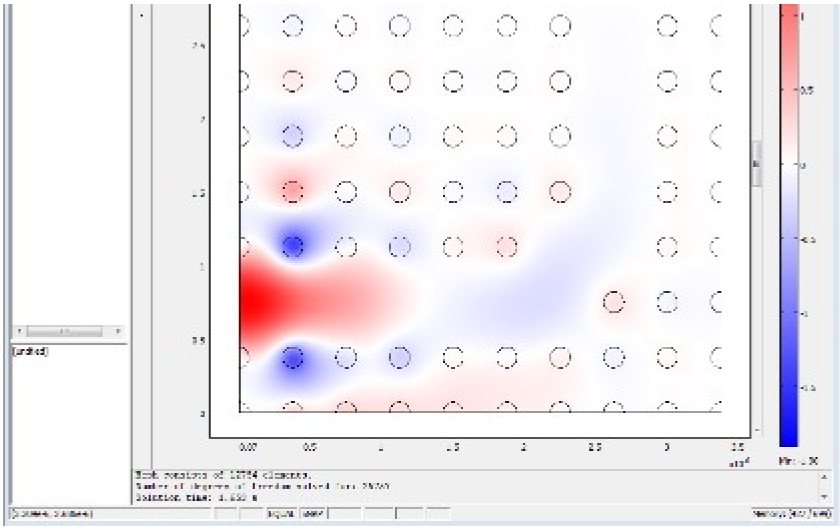
2 Click the **Solve** button.

3 Open the **Plot Parameters** dialog box to change the range of the plot. The WaveLight color table looks best if the range is symmetric around zero.

4 Click the **Range** button, then enter `-1.9` and `1.9` in the **Min** and **Max** edit fields.

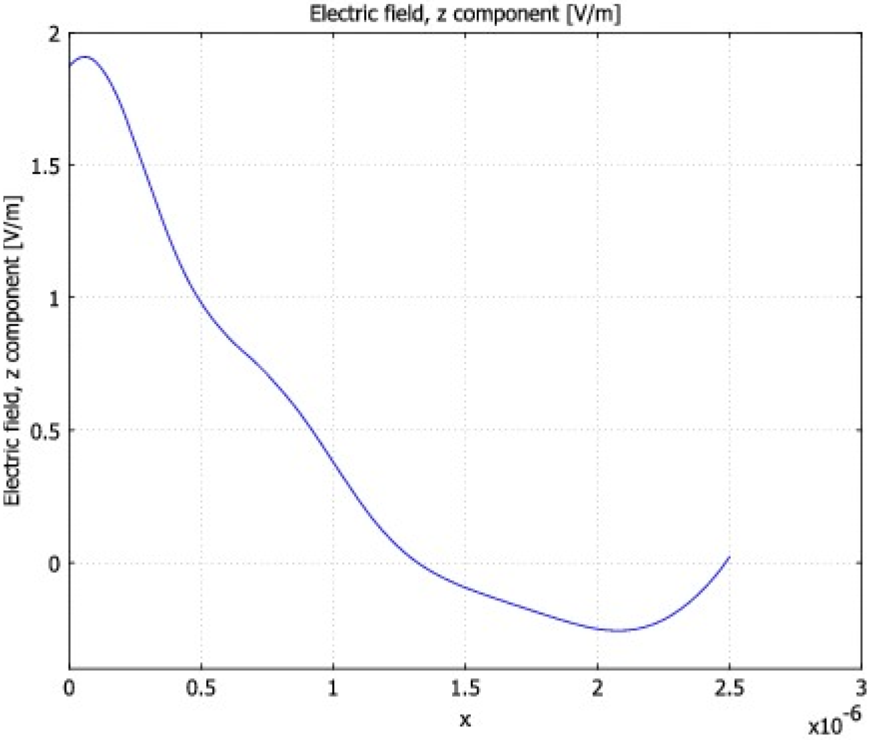
5 Click **OK** twice to see the following plot.





Use a cross-section line plot to visualize the evanescent electric field. Position the plot along the outlined guide between the inlet and the bend.

1. Open the **Cross-Section Plot Parameters** dialog box and select **Line plot**.
2. As **Cross-section line data** set **x0** to `0`, **x1** to `2.5e-6`, **y0** to `0.75e-6`, and **y1** to `0.75e-6`. Set the **x-axis data** to `x`.



The resulting plot shows that the *z* component of the electric field declines exponentially along the plot line.