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Optimization of a Photonic Crystal for Signal Filtering

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 demonstrates how to apply shape optimization to the Photonic Crystal model. The objective function is to increase the ratio of the transmission between two wavelengths. This is achieved by letting the GaAs pillars change position but not shape. The implementation makes use of two shape optimization features, **Free Shape Domain** and **Transformation**, in order to apply gradient-based optimization.

Model Definition

The objective function is defined in terms of the average magnitude of the electric field at the output for a given wavelength and geometry, λ and Ω:

$$\Phi(\lambda) = \int_{\text{output}} |E(\lambda)| ds \Big/ \int_{\text{output}} 1 ds \ .$$

The optimization problem set up in this model is to minimize the log of the ratio between this function for the two wavelengths:

$$\log\left(\frac{\Phi(\lambda_2)}{\Phi(\lambda_1)}\right) = \sum_{\lambda = 1,\ 1.3\ \mu\text{m}} \text{if}(\lambda < 1.15\ \mu\text{m},\text{-}1,1)\log(\Phi(\lambda))\ .$$

The topology of the geometry is fixed to allow for gradient-based optimization. To simplify manufacturing, the shape of the cylinder is also fixed. Thus, the only thing that is allowed to change is the cylinder positions. If they are allowed to move far, they might collide and cause error messages about inverted elements or NaN/Inf values. To avoid this, the cylinders are constrained to move 0.1 µm in the x and y directions.

Results and Discussion

Figure 1 and Figure 2 show the z-component of the electric field in the optimized geometry for the two wavelengths.

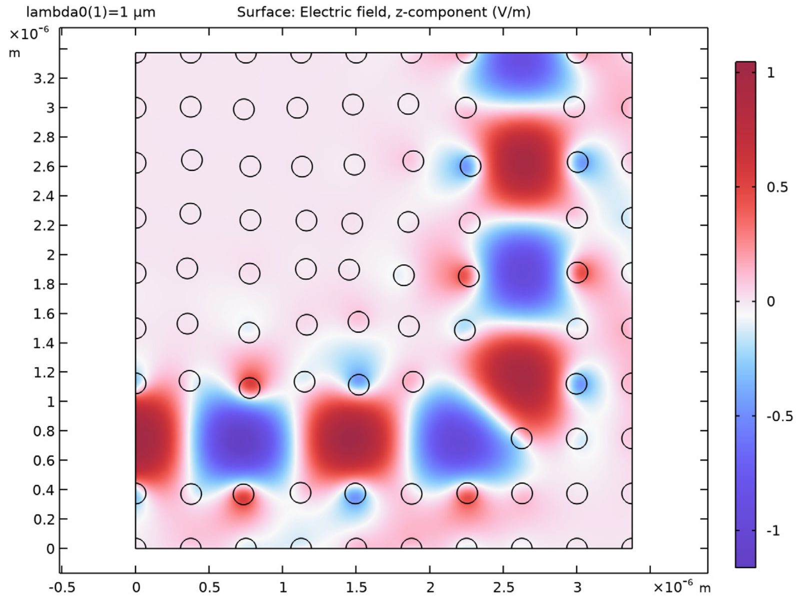

Figure 1: The z-component of the electric field showing how the wave propagates along the path defined by the pillars. The initial geometry consists of a rectangular array of cylinders, so the optimization not only changes the position of the pillars near the wave path.

The optimization increases the transmission for the first wavelength marginally, while reducing the transmission for the second wavelength by 99.9%.

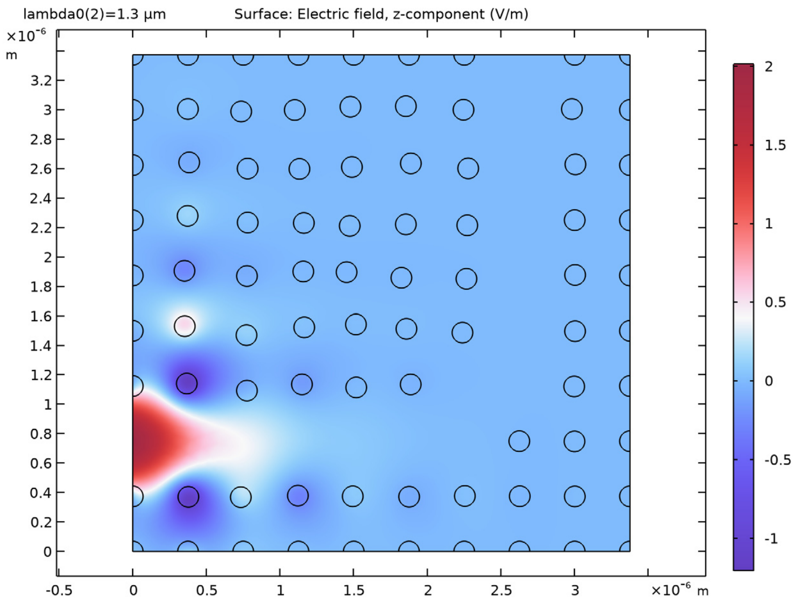

Figure 2: A longer wavelength does not propagate through the guide.

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_filter_optimization`

Modeling Instructions

APPLICATION LIBRARIES

1. From the **File** menu, choose **Application Libraries**.
2. In the **Application Libraries** window, select **Wave Optics Module>Couplers Filters and Mirrors>photonic_crystal** in the tree.

3 Click **Open**.

COMPONENT 1 (COMP1)

Add a probe for the magnitude of the electric field on the output boundary to be used as objective function.

DEFINITIONS

Objective Function

1. In the **Model Builder** window, expand the **Component 1 (comp1)** node.
2. Right-click **Component 1 (comp1)>Definitions** and choose **Probes>Boundary Probe**.
3. In the **Settings** window for **Boundary Probe**, type `Objective Function` in the **Label** text field.
4. In the **Variable name** text field, type `obj`.
5. Locate the **Probe Type** section. From the **Type** list, choose **Integral**.
6. Select Boundary 45 only.
7. Click **Section toolbar** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Energy and power>ewfd.nPoav - Power outflow, time average - W/m²**.

STUDY 1

Step 1: Wavelength Domain

1. In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Wavelength Domain**.
2. In the **Settings** window for **Wavelength Domain**, click to expand the **Results While Solving** section.
3. From the **Probes** list, choose **None**.
4. In the **Model Builder** window, click **Study 1**.
5. In the **Settings** window for **Study**, type `Initial Design` in the **Label** text field.

   Compute the initial values of the objective function, and define parameters corresponding to these values.
6. In the **Home** toolbar, click **Compute**.

RESULTS

Transmission

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

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

Global Evaluation 1

1 Right-click **Transmission** and choose **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)> Definitions>obj - Objective Function - W/m**.

3 In the **Transmission** toolbar, click **Evaluate**.

GEOMETRY 1

Simplify the setup of the shape optimization by adding two selections to the geometry sequence.

Domains to Move

1 In the **Geometry** toolbar, click **Selections** and choose **Box Selection**.

2 In the **Settings** window for **Box Selection**, type `Domains to Move` in the **Label** text field.

3 Locate the **Box Limits** section. In the **x minimum** text field, type `0.2e-6`.

4 In the **x maximum** text field, type `3.2e-6`.

5 In the **y minimum** text field, type `0.2e-6`.

6 In the **y maximum** text field, type `3.2e-6`.

7 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.

Deforming Domains

1 In the **Geometry** toolbar, click **Selections** and choose **Adjacent Selection**.

2 In the **Settings** window for **Adjacent Selection**, type `Deforming Domains` in the **Label** text field.

3 Locate the **Output Entities** section. From the **Geometric entity level** list, choose **Adjacent domains**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog box, select **Domains to Move** in the **Input selections** list.

6 Click **OK**.

COMPONENT 1 (COMP1)

Free Shape Domain 1

1 In the **Physics** toolbar, click **Optimization** and choose **Shape Optimization**.
2 In the **Settings** window for **Free Shape Domain**, locate the **Domain Selection** section.
3 From the **Selection** list, choose **Deforming Domains**.

Transformation 1

1 In the **Shape Optimization** toolbar, click **Transformation**.
2 In the **Settings** window for **Transformation**, locate the **Geometric Entity Selection** section.
3 From the **Selection** list, choose **Domains to Move**.
4 Locate the **Translation** section. From the **Translation type** list, choose **Distance**.
5 In the d_{max} text field, type `0.1[um]`.
6 Locate the **Scaling** section. From the **Scaling type** list, choose **No scaling**.

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 **Preset Studies for Selected Physics Interfaces>Wavelength Domain**.
4 Click **Add Study** in the window toolbar.
5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

INITIAL DESIGN

Step 1: Wavelength Domain

1 In the **Model Builder** window, expand the **Initial Design** node, then click **Step 1: Wavelength Domain**.
2 In the **Settings** window for **Wavelength Domain**, locate the **Physics and Variables Selection** section.
3 In the table, clear the **Solve for** check box for **Deformed geometry (Component 1)**.

STUDY 2

Shape Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Shape Optimization**.

The default move limit of 0.1 is often too conservative, except if the setup of the shape optimization problem introduces too much design freedom. In this case we will double it to save computational time.

2 In the **Settings** window for **Shape Optimization**, locate the **Optimization Solver** section.

3 In the **Maximum number of iterations** text field, type `20`.

4 In the **Move limits** text field, type `0.2`.

5 Locate the **Objective Function** section. In the table, enter the following settings:

Expression	Description
`if(lambda0<1.15[um],-1,1)*log(comp1.obj[m/W])`	

This corresponds to minimizing the transmission at 1.3 µm divided by the transmission at 1 µm.

6 From the **Objective scaling** list, choose **Initial solution based**.

7 Locate the **Output While Solving** section. From the **Probes** list, choose **None**.

8 In the **Model Builder** window, click **Study 2**.

9 In the **Settings** window for **Study**, type `Shape Optimization` in the **Label** text field.

Initialize the study to generate a plot for use while optimizing.

10 In the **Study** toolbar, click **Get Initial Value**.

11 In the **Model Builder** window, click **Shape Optimization**.

12 In the **Settings** window for **Shape Optimization**, locate the **Output While Solving** section.

13 Select the **Plot** check box.

14 From the **Plot group** list, choose **Shape Optimization**.

Solver Configurations

It is easier to converge the problem using a **Segregated** solver.

In the **Model Builder** window, expand the **Shape Optimization>Solver Configurations** node.

Solution 2 (sol2)

1 In the **Model Builder** window, expand the **Shape Optimization>Solver Configurations>Solution 2 (sol2)** node, then click **Optimization Solver 1**.

2 In the **Settings** window for **Optimization Solver**, click to expand the **Advanced** section.

3 From the **Compensate for nojac terms** list, choose **Off**.

4 In the **Model Builder** window, expand the **Shape Optimization>Solver Configurations>Solution 2 (sol2)>Optimization Solver 1>Stationary 1** node.

5 Right-click **Stationary 1** and choose **Segregated**.

6 In the **Settings** window for **Segregated**, locate the **General** section.

7 From the **Termination technique** list, choose **Iterations**.

8 Right-click **Segregated 1** and choose **Segregated Step**.

9 In the **Settings** window for **Segregated Step**, type `Electric Fields` in the **Label** text field.

10 Locate the **General** section. Under **Variables**, click **Add**.

11 In the **Add** dialog box, in the **Variables** list, choose **Electric field (spatial and material frames) (comp1.E)** and **Translation (geometry frame) (comp1.tsf1.move)**.

12 Click **OK**.

13 In the **Model Builder** window, click **Segregated Step**.

14 In the **Settings** window for **Segregated Step**, locate the **General** section.

15 In the **Variables** list, select **Electric field (spatial and material frames) (comp1.E)**.

16 Under **Variables**, click **Delete**.

17 In the **Label** text field, type `Optimization`.

Step 1: Wavelength Domain

1 In the **Model Builder** window, under **Shape Optimization** 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 **Study** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd) 1

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

Surface 1

1 In the **Model Builder** window, expand the **Electric Field (ewfd) 1** 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 (spatial and material frames) - 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**.
6 In the **Electric Field (ewfd) 1** toolbar, click **Plot**.
7 In the **Settings** window for **Surface**, click **Plot Previous**.

Global Evaluation 1

Compute the objective for the optimized design to verify that transmission has increased for the 1 μm case and decreased for the 1.3 μm case.

1 In the **Model Builder** window, under **Results>Transmission** right-click **Global Evaluation 1** and choose **Duplicate**.

Global Evaluation 2

1 In the **Model Builder** window, click **Global Evaluation 2**.
2 In the **Settings** window for **Global Evaluation**, locate the **Data** section.
3 From the **Dataset** list, choose **Shape Optimization/Solution 2 (sol2)**.
4 In the **Transmission** toolbar, click **Evaluate**.

Thumbnail

Construct a plot for the model thumbnail.

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.
2 In the **Settings** window for **2D Plot Group**, type `Thumbnail` in the **Label** text field.
3 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

Line 1

1 Right-click **Thumbnail** and choose **Line**.
2 In the **Settings** window for **Line**, locate the **Coloring and Style** section.
3 From the **Line type** list, choose **Tube**.
4 In the **Tube radius expression** text field, type `3e-9`.
5 Select the **Radius scale factor** check box.
6 From the **Coloring** list, choose **Uniform**.
7 From the **Color** list, choose **Gray**.

Filter 1

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

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

3 In the **Logical expression for inclusion** text field, type `(5e-7<Xg)*(Yg<28e-7)*(7e-7<Yg)`.

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 **Data** section.

3 From the **Dataset** list, choose **Shape Optimization/Solution 2 (sol2)**.

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

Arrow Line 1

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

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

3 From the **Dataset** list, choose **Shape Optimization/Solution 2 (sol2)**.

4 Locate the **Expression** section. In the **X-component** text field, type `material.dX`.

5 In the **Y-component** text field, type `material.dY`.

6 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type `1e3`.

7 Locate the **Coloring and Style** section. From the **Arrow base** list, choose **Head**.

8 Select the **Scale factor** check box. In the associated text field, type `1`.

Filter 1

In the **Model Builder** window, under **Results>Thumbnail>Line 1** right-click **Filter 1** and choose **Copy**.

Arrow Line 1

In the **Model Builder** window, under **Results>Thumbnail** right-click **Arrow Line 1** and choose **Paste Filter**.

Color Expression 1

1 In the **Model Builder** window, right-click **Arrow Line 1** and choose **Color Expression**.

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

3 In the **Expression** text field, type `sqrt(material.dX^2+material.dY^2)`.

4 Locate the **Coloring and Style** section. Clear the **Color legend** check box.

5 In the **Thumbnail** toolbar, click **Plot**.