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Optical Ring Resonator Notch Filter

Introduction

The simplest optical ring resonator consists of a straight waveguide and a ring waveguide. The two waveguide cores are placed close to each other, so light couples from one waveguide to the other.

When the length of the ring waveguide is a integer number of wavelengths, the ring waveguide is resonant to the wavelength and the light power stored in the ring builds up.

The wave transmitted through the straight waveguide is the interference of the incident wave and the wave that couples over from the ring to the straight waveguide.

Schematically, you can think of the ring resonator as shown in Figure 1 below. A part of the incident wave $\boldsymbol{E}_{i1}$ is transmitted in the straight waveguide, whereas a fraction of that field couples over to the ring. Similarly, some of the light in the ring couples over to the straight waveguide, whereas the rest of that wave continuous around the ring waveguide.

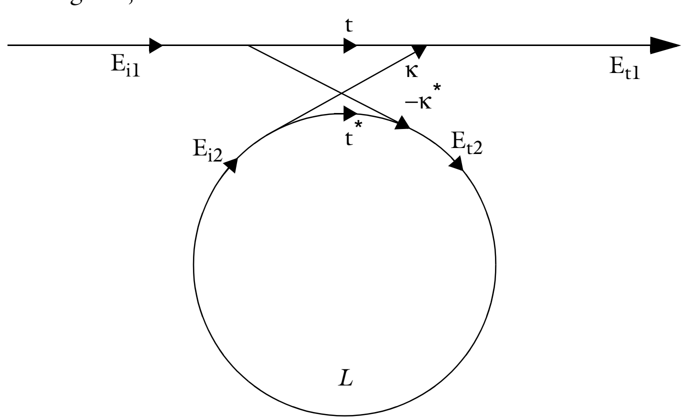


Figure 1: Schematic of an optical ring resonator, showing the incident fields E_{i1} and E_{i2} and the transmitted/coupled fields E_{t1} and E_{t2}. The transmission and coupling coefficients t and κ are also indicated, as well as the round-trip loss L.

The transmitted fields are related to the incident fields through the matrix-vector relation

$$\begin{bmatrix} E_{t1} \\ E_{t2} \end{bmatrix} = \begin{bmatrix} t & \kappa \\ -\kappa^* & t^* \end{bmatrix} \begin{bmatrix} E_{i1} \\ E_{i2} \end{bmatrix}. \tag{1}$$

The matrix elements defined above, assures that the total input power equals the total output power,

$$|E_{t1}|^2 + |E_{t2}|^2 = |E_{i1}|^2 + |E_{i2}|^2, \quad (2)$$

by assuming that coupler's transmission and coupling coefficients are related by

$$|t|^2 + |\kappa|^2 = 1. \quad (3)$$

Furthermore, as the wave propagates around the ring waveguide, you get the relation

$$E_{i2} = E_{t2} L \exp(-j\phi), \quad (4)$$

where L is the loss coefficient for the propagation around the ring and ϕ is the accumulated phase.

Combining Equation 1, Equation 3 and Equation 4, the transmitted field can be written

$$E_{t1} = \frac{|t| - L\exp(-j(\phi - \phi_t))}{1 - |t|L\exp(-j(\phi - \phi_t))} E_{i1} e^{-j\phi_t}. \quad (5)$$

Here the transmission coefficient is separated into the transmission loss $|t|$ and the corresponding phase ϕ_t,

$$t = |t| e^{-j\phi_t}. \quad (6)$$

Notice, that on resonance, when ϕ - ϕ_t is an integer number times 2π, and when $|t| = L$, the transmitted field is zero. The condition that $|t| = L$ is called critical coupling. Thus, when the coupler's transmission loss balances the loss for the wave propagating around the ring waveguide you get the optimum condition for a bandstop filter, a notch filter.

Model Definition

This application is setup using the Electromagnetic Waves, Beam Envelopes physics interface, to handle the propagation over distances that are many wavelengths long. Since the wave propagates in essentially one direction along the straight waveguide and along the waveguide ring, the unidirectional formulation is used. This assumes that the electric field for the wave can be written as

$$\mathbf{E} = \mathbf{E}_1 \exp(-j\phi), \quad (7)$$

where $\mathbf{E}_1$ is a slowly varying field envelope function and ϕ is an approximation of the propagation phase for the wave. The definitions used for the phase in the straight and ring waveguide are shown in Table 1 and Table 2.

TABLE 1: PHASE DEFINITION IN STRAIGHT WAVEGUIDE DOMAINS.

NAME	EXPRESSION	UNIT	DESCRIPTION
phi	ewbe.beta_1*y	rad	Phase

TABLE 2: PHASE DEFINITION IN RING WAVEGUIDE DOMAINS.

NAME	EXPRESSION	UNIT	DESCRIPTION
phi	ewbe.beta_1*r0*atan2(-y,x)	rad	Phase

Notice in Figure 2 that the phase approximation defined in Table 1 and in Table 2 is discontinuous at the boundary between the straight waveguide and the ring waveguide. To handle this phase discontinuity and thereby the discontinuity in the field envelope, $\mathbf{E}_1$, a FieldContinuity boundary condition is used at the boundary between the straight waveguide and the ring waveguide. This boundary condition ensures that the tangential components of the electric and the magnetic fields are continuous at the boundary, despite the phase jump.

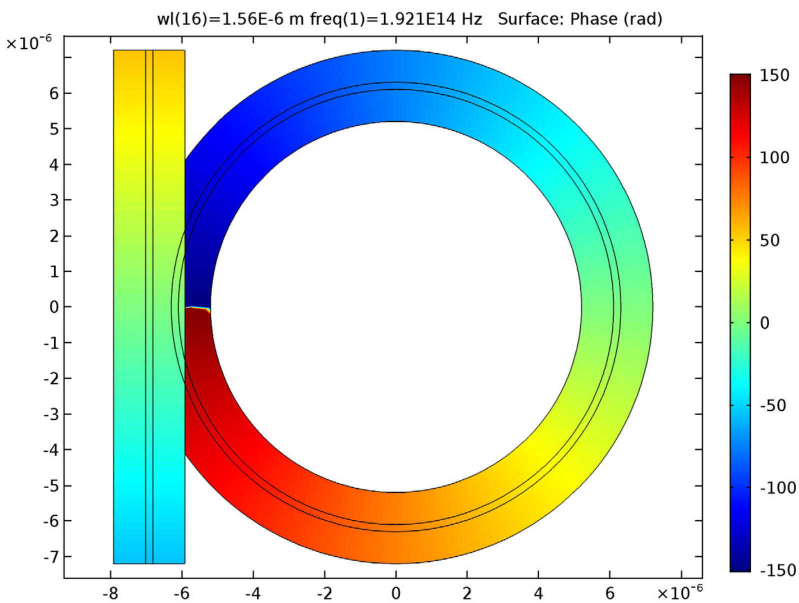


Figure 2: Plot of the pre-defined phase approximation. Notice that the phase jump at y = 0 in the cladding of the left part of the ring waveguide is neglected, as the light is mainly confined to the waveguide core.

Figure 3 below shows the transmittance spectrum for the optical ring resonator

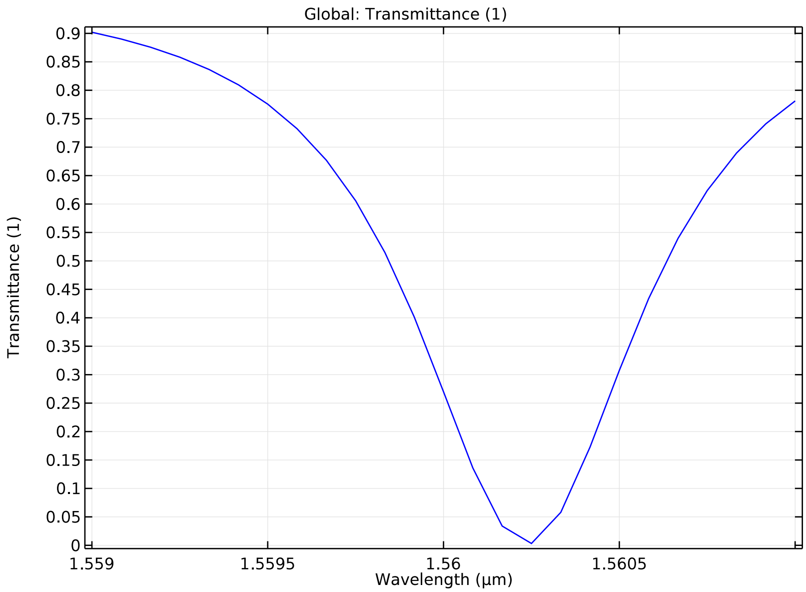


Figure 3: Transmittance spectrum for the optical ring resonator.

and Figure 4 shows a field plot for a resonant wavelength. Notice that the field in the straight waveguide and the field incoming from the ring is out-of-phase, when they interfere in the coupler. Thereby the outgoing field in the straight waveguide is almost zero.

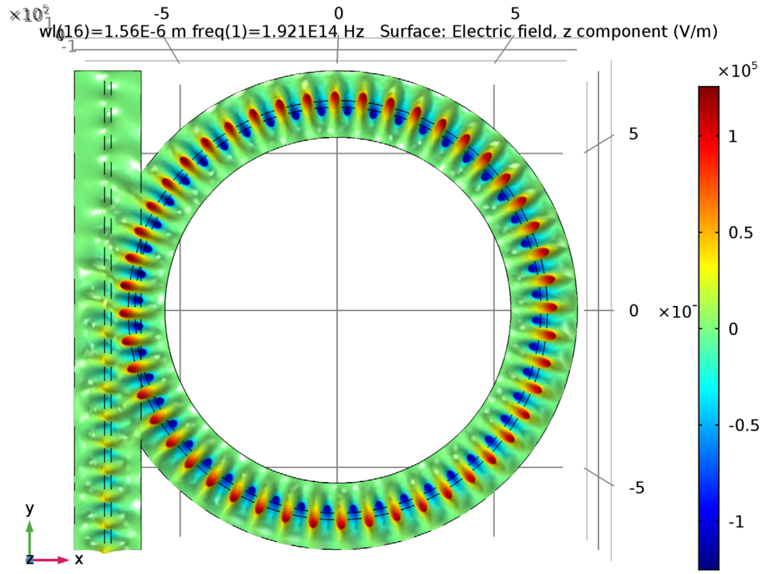


Figure 4: The out-of-plane component of the electric field for the resonant wavelength.

Application Library path: `Wave_Optics_Module/Waveguides_and_Couplers/optical_ring_resonator`

Model Instructions

First add the physics interface and the study sequence.

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, Beam Envelopes (ewbe)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies>Boundary Mode Analysis**.

6 Click **Done**.

GEOMETRY 1

The geometry for the optical ring resonator is quite complicated to set up. To get straight to the physics modeling, start by importing the geometry sequence. In the imported MPH-file, the parameters for the geometry are already defined.

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

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

GLOBAL DEFINITIONS

Start by loading a few more parameters required for building the physics and defining the materials.

Parameters

1 On the **Home** toolbar, click **Parameters**.

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

3 Click **Load from File**.

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

DEFINITIONS

Now add the definitions for the phase in the two waveguide domains.

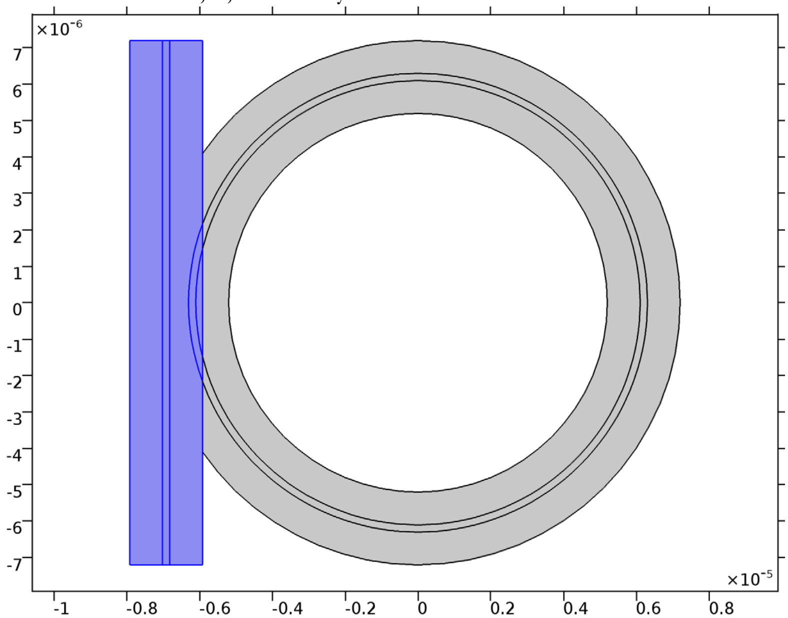
Variables 1

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

2 In the **Settings** window for Variables, type `Phase, straight waveguide` in the **Label** text field.

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

4 Select Domains 1–3, 6, and 8 only.



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

Name	**Expression**	**Unit**	**Description**
`phi`	`ewbe.beta_1*y`		

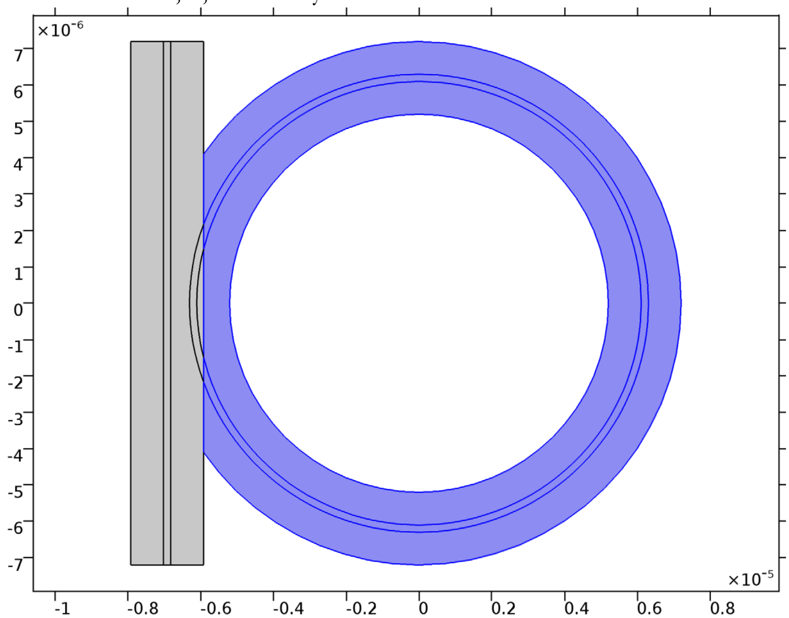
Variables 2

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

2 In the **Settings** window for Variables, type `Phase, ring waveguide` in the **Label** text field.

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

4 Select Domains 4, 5, and 7 only.



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

Name	Expression	Unit	Description
phi	ewbe.beta_1*r0*atan2(-y,x)		

MATERIALS

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

Material 1 (mat1)

1 In the **Settings** window for Material, type `Cladding` in the **Label** text field.

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

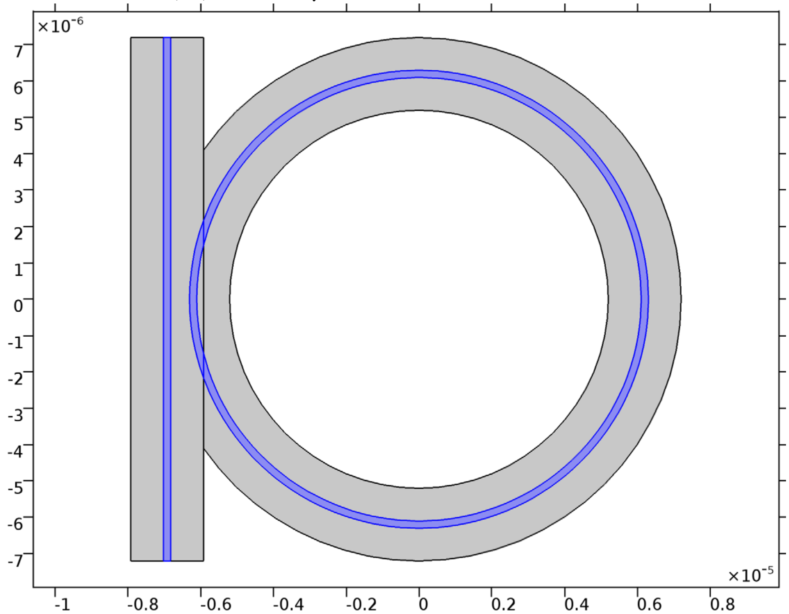
Property	Name	Value	Unit	Property group
Refractive index	n	n_clad	1	Refractive index

Material 2 (mat2)

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

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

3 Select Domains 2, 5, and 6 only.



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

Property	Name	Value	Unit	Property group
Refractive index	n	`n_core`	1	Refractive index

ELECTROMAGNETIC WAVES, BEAM ENVELOPES (EWBE)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Beam Envelopes (ewbe)**.

2 In the **Settings** window for Electromagnetic Waves, Beam Envelopes, locate the **Wave Vectors** section.

3 From the **Number of directions** list, choose **Unidirectional**.

4 From the **Type of phase specification** list, choose **User defined**.

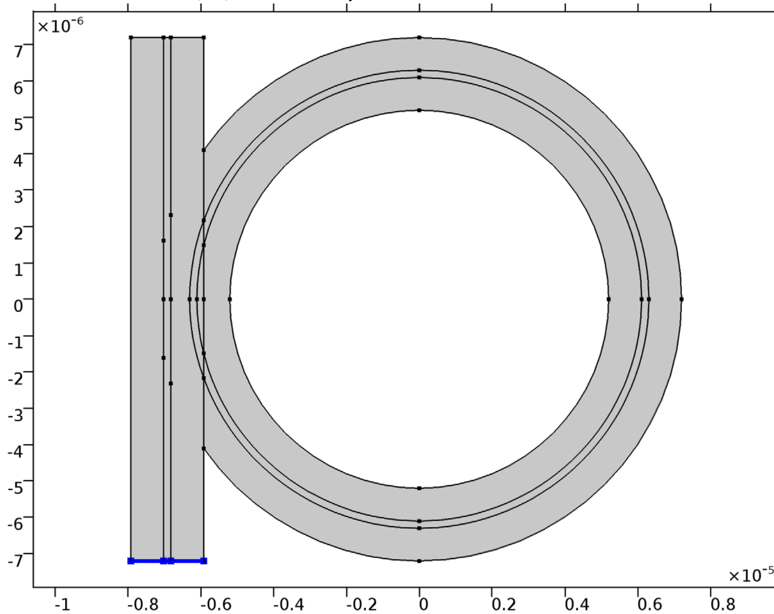
5 In the ϕ_1 text field, type `phi`.

Port 1

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

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

3 Select Boundaries 2, 5, and 11 only.



4 In the **Settings** window for Port, locate the **Port Properties** section.

5 From the **Type of port** list, choose **Numeric**.

6 From the **Wave excitation at this port** list, choose **On**.

Port 2

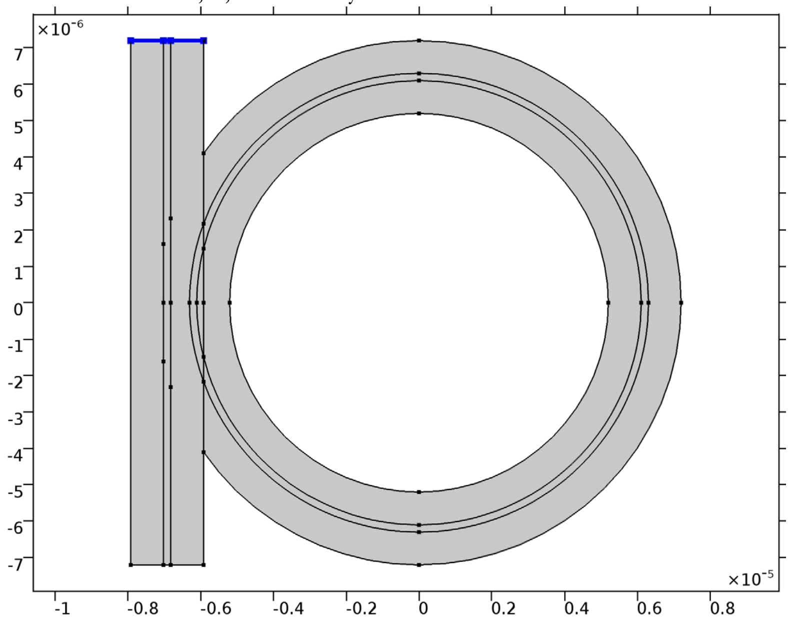
1 In the **Model Builder** window, right-click **Port 1** and choose **Duplicate**.

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

3 Click **Clear Selection**.

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

5 Select Boundaries 3, 9, and 15 only.

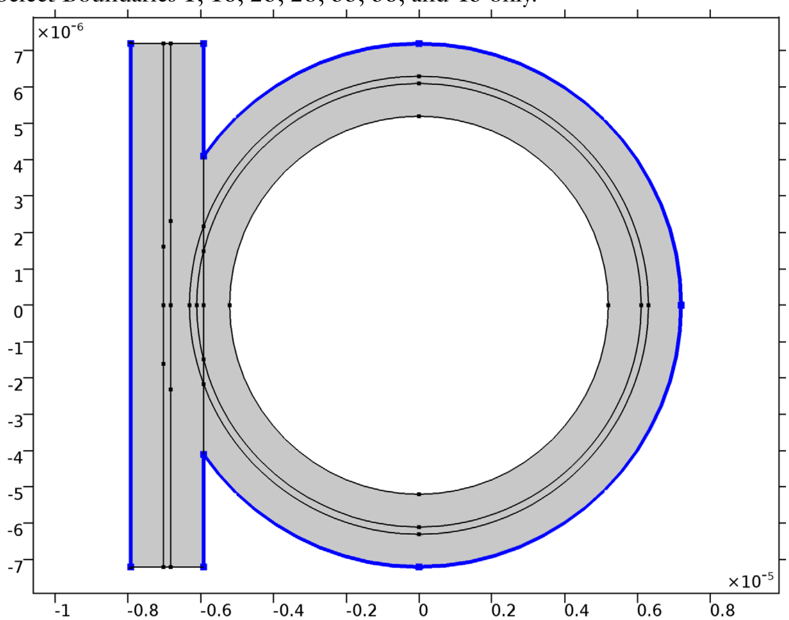


6 Locate the **Port Properties** section. From the **Wave excitation at this port** list, choose **Off**.

Scattering Boundary Condition 1

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

2 Select Boundaries 1, 16, 23, 28, 33, 36, and 43 only.



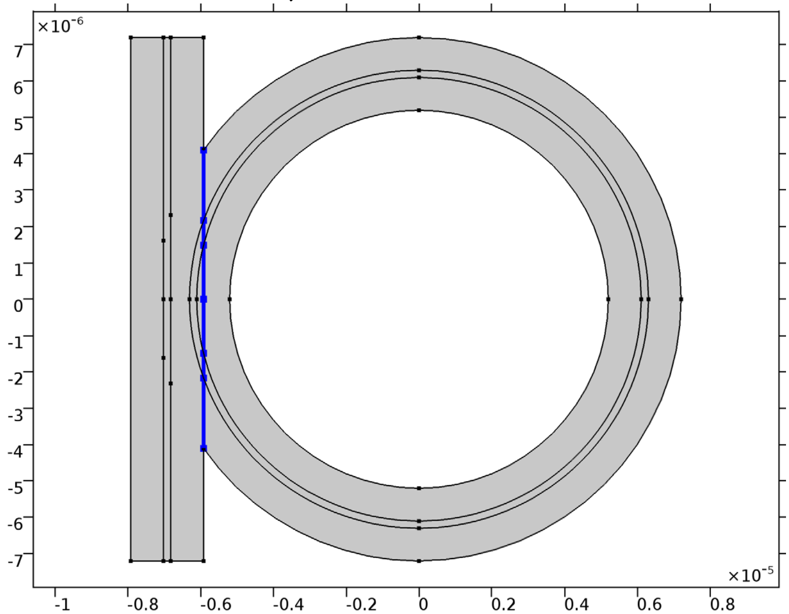
3 In the **Model Builder** window's toolbar, click the **Show** button and select **Advanced Physics Options** in the menu.

Field Continuity 1

1 On the **Physics** toolbar, click **Boundaries** and choose **Field Continuity**.

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

3 Select Boundaries 17–22 only.



MESH 1

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

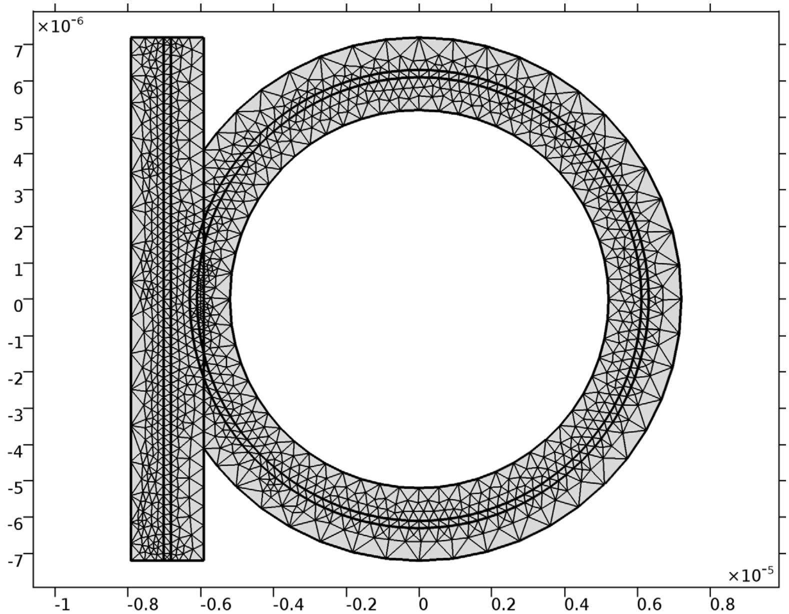
Size

1 In the **Settings** window for Size, locate the **Element Size** section.

2 Click the **Custom** button.

3 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `w_clad/2`.

4 Click **Build All**.



STUDY 1

Step 1: Boundary Mode Analysis

1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Boundary Mode Analysis**.

2 In the **Settings** window for Boundary Mode Analysis, locate the **Study Settings** section.

3 In the **Mode analysis frequency** text field, type `f0`.

4 Select the **Search for modes around** check box.

5 In the associated text field, type `n_core`.

Step 3: Boundary Mode Analysis 1

1 Right-click **Study 1>Step 1: Boundary Mode Analysis** and choose **Duplicate**.

2 In the **Settings** window for Boundary Mode Analysis, locate the **Study Settings** section.

3 In the **Port name** text field, type `2`.

Step 2: Frequency Domain

1 In the **Model Builder** window, under **Study 1** click **Step 2: Frequency Domain**.

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

3 In the **Frequencies** text field, type `f0`.

Parametric Sweep

1 Right-click **Study 1>Step 2: Frequency Domain** and choose **Move Down**.

2 On the **Study** toolbar, click **Parametric Sweep**.

3 In the **Settings** window for Parametric Sweep, locate the **Study Settings** section.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
wl		

6 Click **Range**.

7 In the **Range** dialog box, choose **Number of values** from the Entry method list.

8 In the **Start** text field, type `1.559[um]`.

9 In the **Stop** text field, type `1.561[um]`.

10 In the **Number of values** text field, type `25`.

11 Click **Replace**.

12 On the **Study** toolbar, click **Compute**.

RESULTS

Electric Field

1 In the **Model Builder** window, expand the **Electric Field (ewbe)** node, then click **Electric Field**.

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

3 In the **Expression** text field, type `ewbe.Ez`.

4 Right-click **Results>Electric Field (ewbe)>Electric Field** and choose **Height Expression**.

Height Expression 1

Click the **Go to XY View** button on the **Graphics** toolbar.

Electric Field (ewbe)

1 In the **Model Builder** window, under **Results** click **Electric Field (ewbe)**.

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

3 From the **Parameter value (wl (m))** list, choose **1.5603E-6 (1)**.

4 On the **Electric Field (ewbe)** toolbar, click **Plot**.

5 Click the **Zoom Extents** button on the **Graphics** toolbar. The plot should now look like Figure 4.

1D Plot Group 2

1 On the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 From the **Data set** list, choose **Study 1/Parametric Solutions 1 (sol4)**.

Global 1

1 On the **1D Plot Group 2** toolbar, click **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`abs(ewbe.S21)^2`	`1`	`Transmittance`

4 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Outer solutions**.

5 From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `wl`.

7 From the **Unit** list, choose **µm**.

8 On the **1D Plot Group 2** toolbar, click **Plot**.

1D Plot Group 2

1 In the **Model Builder** window, under **Results** click **1D Plot Group 2**.

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

3 Select the **x-axis label** check box.

4 In the associated text field, type `Wavelength (µm)`.

5 Click to expand the **Legend** section. Clear the **Show legends** check box. The plot should now look like Figure 3.