Created in COMSOL Multiphysics 6.2

Fast Prototyping of a Butler Matrix Beamforming Network

Introduction

A Butler matrix is a passive beamforming feed network. It is a cost-effective feed network for phased array antennas because the circuit can be fabricated in the form of microstrip lines and it is viable to perform beam scanning without deploying expensive active devices. This example guides how to design such a circuit efficiently using the Transmission Line physics interface. The results show the logarithmic voltage on the Butler matrix beamforming circuit at 30 GHz and the arithmetic phase progression at each output port.

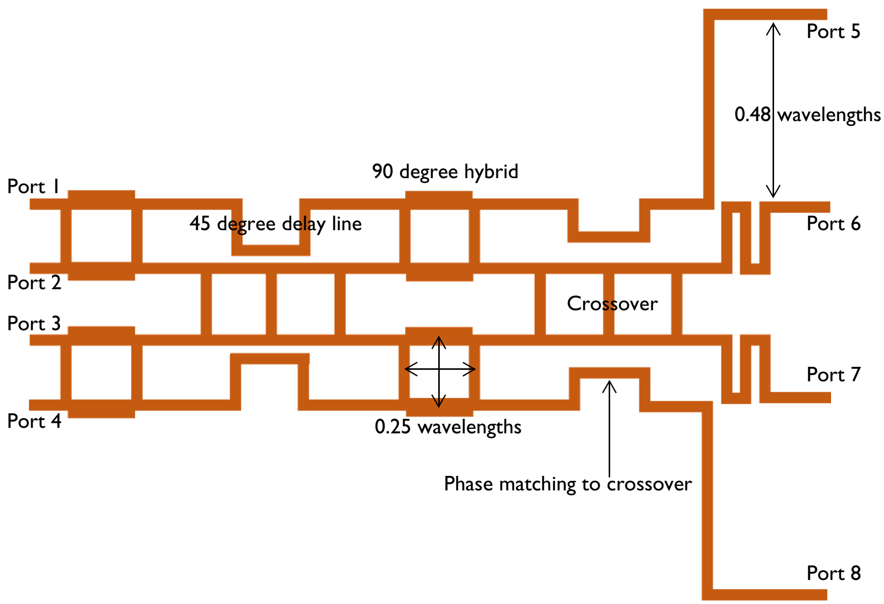


Figure 1: A microstrip 4×4 Butler matrix beamforming network for a phased array antenna

Model Definition

The butler matrix beamforming network consists of a few subsections: 90 degree hybrid, 45 degree delay line, crossover, transition matching the output phase to that of crossover, and inner and outer front-ends. Since these subsections are repeatedly used in the entire structure, the geometry building process can be simplified by adding these subsections as the Geometry Parts under Global Definition node and reusing them as necessary.

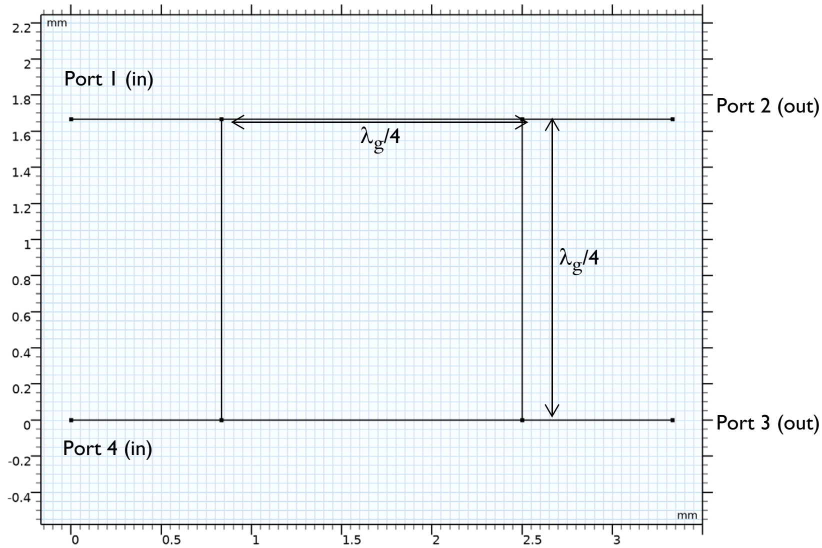


Figure 2: The part geometry of a 90 degree hybrid (branch-line coupler)

The geometry of a 90 degree hybrid, also known as a branch-line coupler is shown in Figure 2. Ref. 1 discusses the design characteristics and its S-parameters calculated using even-odd model analysis. A full 3D COMSOL model is available in Ref. 2. The 90 degree hybrid splits the input power equally into two output ports (-3 dB) with a 90 degree phase difference. Because the geometry is symmetric, the response of the circuit is reciprocal regardless of the input port configuration. In this example, the input ports are located on the left side and there is no coupled power between the input ports that is also described by its S-parameter matrix:

$$[S] = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

Figure 3 describes a delay line geometry providing a 45 degrees phase lag than the output phase of the crossover. Figure 4 shows a transition part that matches the output phase to that of the crossover.

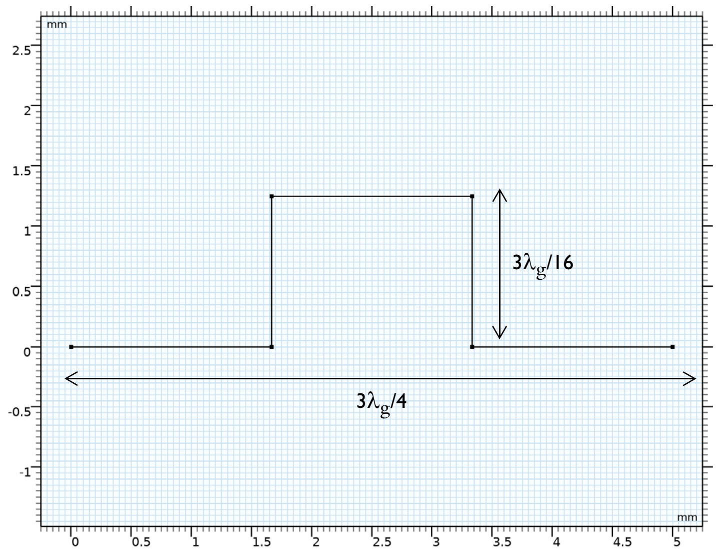


Figure 3: The part geometry of a 45 degree delay line that is 0.125 wavelengths longer than the crossover part.

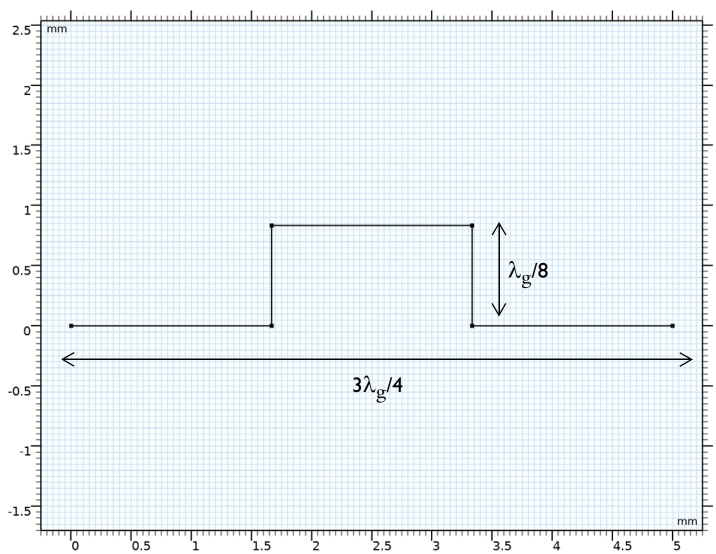


Figure 4: The part geometry of a transition structure. The electrical length is same as that in the input signal path of the crossover part.

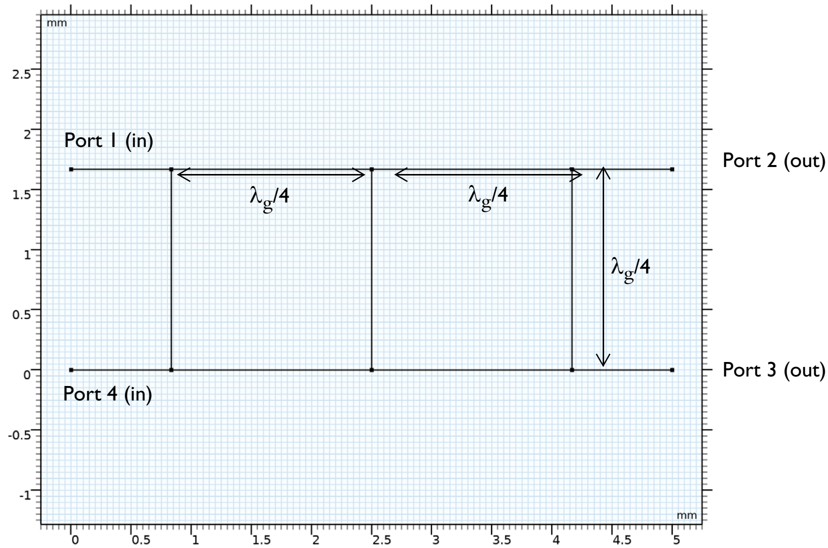


Figure 5: The part geometry of a crossover structure. The port definition is only for the subsection analysis.

The geometry of a crossover in Figure 5 is analogous of a two-section cascaded branch-line coupler, but it consists of only 50 Ω lines. Its behavior can be analyzed with the same even-odd analysis method (Ref. 1) used for the branch-line coupler characterization. The even-odd analysis transforms the four-port network into two decoupled two-port networks. After the transformation, each cascaded two-port network can be described via ABCD parameters.

If the circuit is normalized by the 50 Ω reference impedance, the ABCD parameters for each section are

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{open, shunt}} = \begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{short, shunt}} = \begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{50\Omega,\,\frac{\lambda}{4}\text{line}} = \begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{even}} = \begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix}\begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix}\begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ j & 1 \end{bmatrix} = \begin{bmatrix} 0 & -j \\ -j & 0 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{odd}} = \begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix}\begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix}\begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -j & 1 \end{bmatrix} = \begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}$$

The reflection and transmission coefficients from ABCD are defined as

$$\Gamma = \frac{A+B-C-D}{A+B+C+D}$$

$$T = \frac{2}{A+B+C+D}$$

The wave amplitude at each port is

$$B_1 = (\Gamma_{\text{even}} + \Gamma_{\text{odd}})/2 = 0$$

$$B_2 = (T_{\text{even}} + T_{\text{odd}})/2 = 0$$

$$B_3 = (T_{\text{even}} - T_{\text{odd}})/2 = j$$

$$B_4 = (\Gamma_{\text{even}} - \Gamma_{\text{odd}})/2 = 0$$

Because it is a passive and reciprocal network, the S-parameters are

$$[S] = \begin{bmatrix} 0 & 0 & j & 0 \\ 0 & 0 & 0 & j \\ j & 0 & 0 & 0 \\ 0 & j & 0 & 0 \end{bmatrix}$$

The two input ports are isolated from each other. The input signal from the upper left side flows to the output at the lower right side while the input signal from the lower left side flows to the output at the upper right side. The ladder-shape crossover structure works like X-shape crossover lines.

Figure 6 and Figure 7 show the geometry of front-end parts that adjust the distance between output ports from a quarter-wavelength to 0.48 wavelengths without distorting the output phase relation. The higher gain of an antenna array can be realized by increasing the distance between antenna elements, but this will result in an undesirable higher sidelobe level and a grating lobe. The given spacing configuration for antenna array elements provides the antenna radiation pattern with a reasonable gain and sidelobe level.

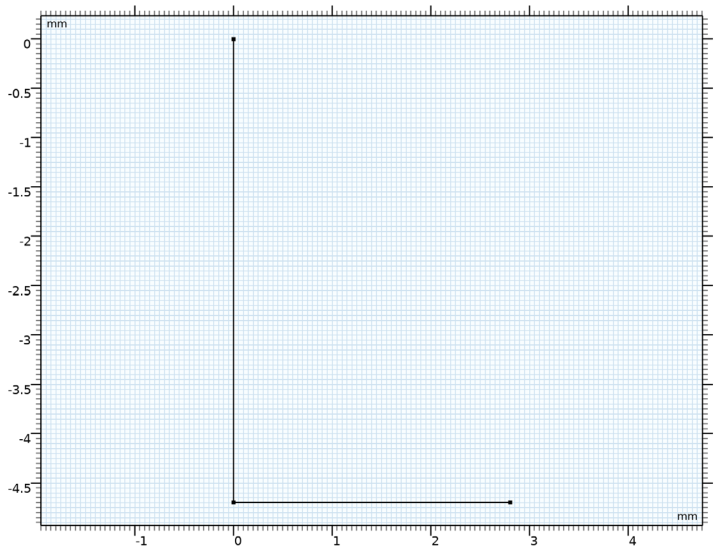


Figure 6: The part geometry of an outer front-end structure.

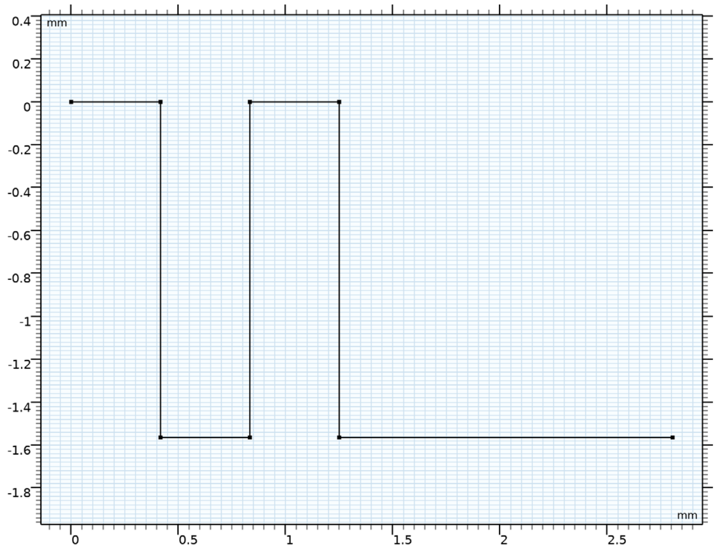


Figure 7: The part geometry of an inner front-end structure.

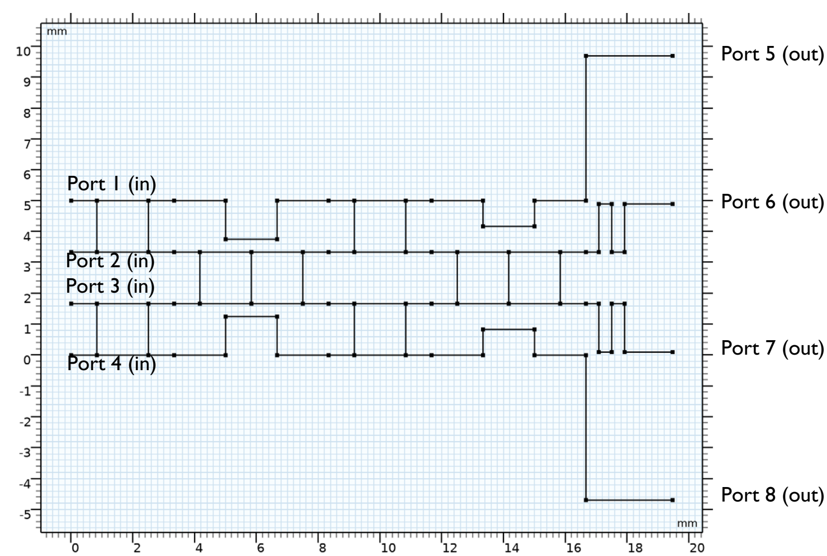


Figure 8: The finalized geometry of a butler matrix beamforming network.

By combining four 90 degree hybrids (branch-line couplers), two 45 degree delay lines, two phase matching transitions, two inner front ends, and two outer front ends, the geometry for the butler matrix beamforming network is completed (Figure 8).

All transmission line distributed element parameters except for a few branch-lines are set based on a 50 Ω microstrip line built on a 20 mil lossless substrate with permittivity ε_r = 3.38 and 1 oz copper. The accurate values can be calculated accurately from Ref. 3.

TABLE 1: CALCULATED TRANSMISSION LINE PARAMETERS OF A 50 Ω MICROSTRIP LINE.

R	L	G	C
12.41 Ω/m	272.9 nH/m	0 S/m	107.1 pF/m

The contribution of the distributed resistance on the insertion loss with the given substrate properties is less than 0.05 dB. To make the modeling steps simpler in this example, the approximated parameter values in Table 2 are used for a 50 Ω microstrip line.

TABLE 2: SIMPLIFIED TRANSMISSION LINE PARAMETERS OF A 50 Ω MICROSTRIP LINE.

R	L	G	C
0 Ω/m	250 nH/m	0 S/m	100 pF/m

The transmission line parameters with a different characteristic impedance value, $Z_0/\sqrt{2}$ for the branch-lines, are adjusted using the normalized impedance. The distributed inductance is proportionally scaled and the distributed capacitance is inversely scaled by the normalized impedance of the microstrip line.

In order to excite ports one by one, the port sweep option in the transmission line physics interface is activated and combined with a parametric sweep in the study steps. Each port is terminated by a lumped port with 50 Ω reference characteristic impedance.

Results and Discussion

The default plot show the real value of the voltage on the transmission lines. The default input expression is changed to plot the logarithmic value of the voltage (Figure 9). The plot shows that port 1, port 2, and port 3 have no coupled power (below –100 dB) from the excited port 4.

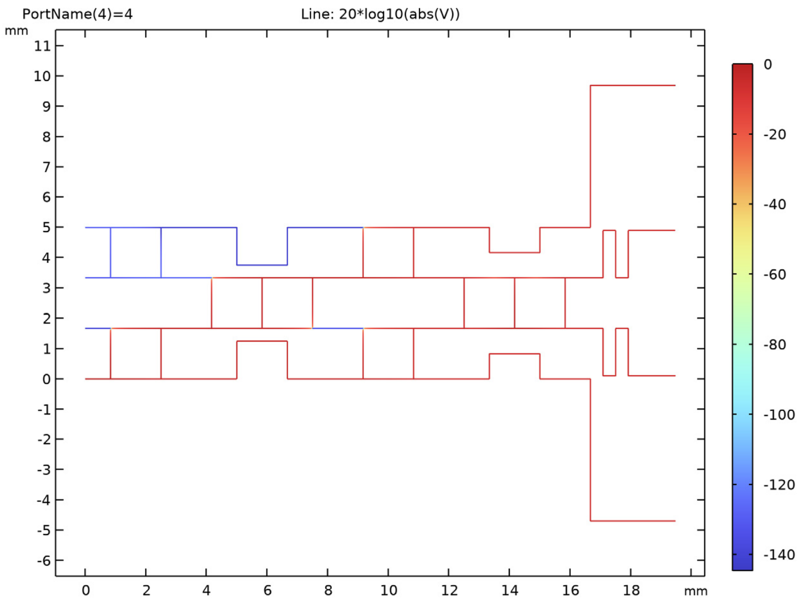


Figure 9: The dB-scaled voltage on the transmission lines when port 4 is excited. Port1, port 2 and port 3 are isolated below -100 dB.

In Figure 10, the minimum range of the dB-scaled voltage plot is set to –10 dB to get a closer look at the level of each output port. The input voltage is equally distributed to all four output ports (–6 dB).

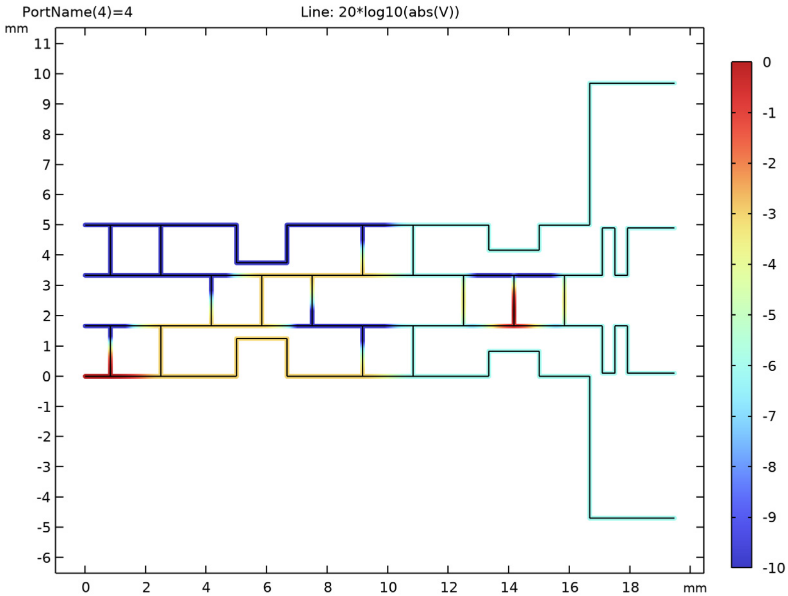


Figure 10: The range of the dB-scaled voltage plot is adjusted to see the output voltage level.

Table 3 shows the evaluated phase at each output port.

TABLE 3: THE EVALUATED PHASE OF VOLTAGE AT EACH PORT.

	PORT 5	PORT 6	PORT 7	PORT 8
PORT 1 EXCITED	-90°	-135°	-180°	135°
PORT 2 EXCITED	-180°	-45°	90°	-135°
PORT 3 EXCITED	-135°	90°	-45°	-180°
PORT 4 EXCITED	135°	-180°	-135°	-90°

By adjusting some of the evaluated angles, the phase at each port can be configured in an arithmetic order and the resulted phase progression is summarized in Table 4. If the butler matrix beamforming network is excited in the order of port 3 (–135 degrees), port 1 (–45 degrees), port 4 (45 degrees), and port 2 (135 degrees), and connected to a 4×1 antenna array, the antenna radiation pattern will be steered from one side to the other side (Figure 11). Note that the antenna array model in Figure 11 is not included in this example.

TABLE 4: THE EVALUATED PHASE OF VOLTAGE AT EACH PORT (PHASE ADJUSTED).

	PORT 5	PORT 6	PORT 7	PORT 8	PHASE PROGRESSION
PORT 1 EXCITED	-90°	-135°	-180°	-225°	-45°
PORT 2 EXCITED	-180°	-45°	90°	225°	135°
PORT 3 EXCITED	225°	90°	-45°	180°	-135°
PORT 4 EXCITED	-225°	-180°	-135°	-90°	45°

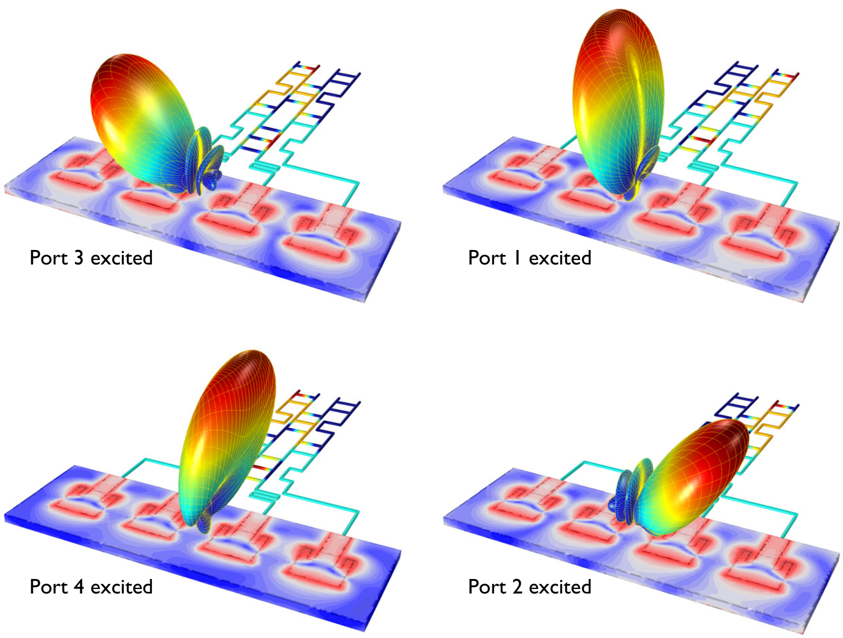


Figure 11: The far-field radiation pattern of a 4×1 microstrip patch antenna array connected to the butler matrix beamforming network. The antenna model is not included in this example.

References

1. D.M. Pozar, *Microwave Engineering*, John Wiley & Sons, 1998.

2. COMSOL Application Gallery, "*Branch-Line Coupler*", https://www.comsol.com/model/branch-line-coupler-11727

3. COMSOL Application Gallery, "*Transmission Line Parameter Calculator*", https://www.comsol.com/model/transmission-line-parameter-calculator-22351

Application Library path: `RF_Module/Couplers_and_Power_Dividers/transmission_line_butler`

Model 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 **Radio Frequency>Transmission Line (tl)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Frequency Domain**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

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

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

3 Click **Load from File**.

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

   Here, `c_const` in the imported table is a predefined COMSOL constant for the speed of light in vacuum.

The 4x4 Butler matrix beamforming network in this example consists of a few parts that are repeatedly shown in the geometry. To make the modeling process more efficient, define these as **Geometry Parts** and reuse them as necessary.

90 DEGREE HYBRID

1 In the **Model Builder** window, right-click **Global Definitions** and choose **Geometry Parts> 2D Part**.

2 In the **Settings** window for **Part**, type `90 Degree Hybrid` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 In the **x** text field, type `ul*2`.

Line Segment 2 (ls2)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 Locate the **Starting Point** section. In the **x** text field, type `ul/2`.

6 Locate the **Endpoint** section. In the **x** text field, type `ul/2`.

7 In the **y** text field, type `ul`.

Rotate 1 (rot1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Rotate**.

2 Click the **Select All** button in the **Graphics** toolbar.

3 In the **Settings** window for **Rotate**, locate the **Rotation** section.

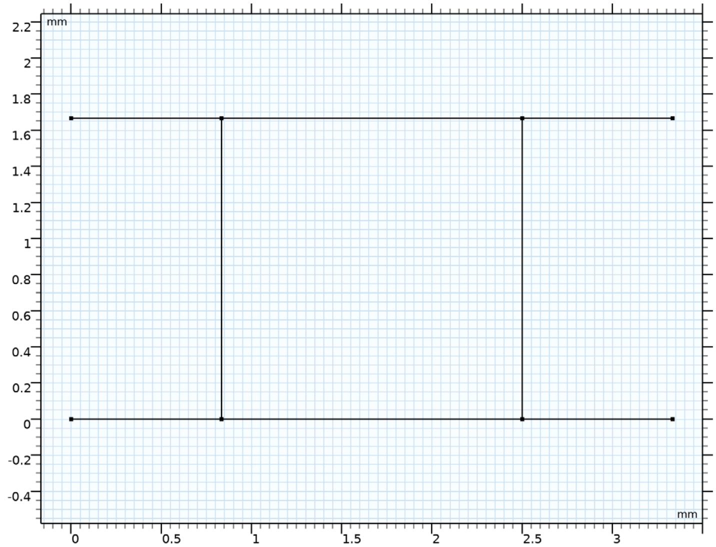
4 In the **Angle** text field, type `0 180`.

5 Locate the **Center of Rotation** section. In the **x** text field, type `ul`.

6 In the **y** text field, type `ul/2`.

7 Click **Build Selected**.

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



45 DEGREE DELAY

1 In the **Model Builder** window, under **Global Definitions** right-click **Geometry Parts** and choose **2D Part**.

2 In the **Settings** window for **Part**, type `45 Degree Delay` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

Polygon 1 (pol1)

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

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

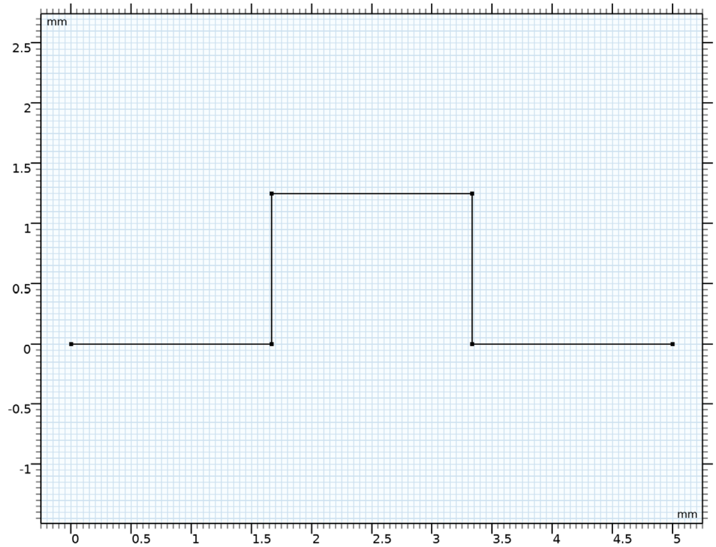
3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. From the **Data source** list, choose **Vectors**.

5 In the **x** text field, type `0 ul ul ul ul ul*2 ul*2 ul*2 ul*2 ul*3`.

6 In the **y** text field, type `0 0 0 ul*0.75 ul*0.75 ul*0.75 ul*0.75 0 0 0`.

7 Click **Build Selected**.



TRANSITION

1 Right-click **Geometry Parts** and choose **2D Part**.

2 In the **Settings** window for **Part**, type `Transition` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

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

1 In the **Settings** window for **Polygon**, locate the **Object Type** section.

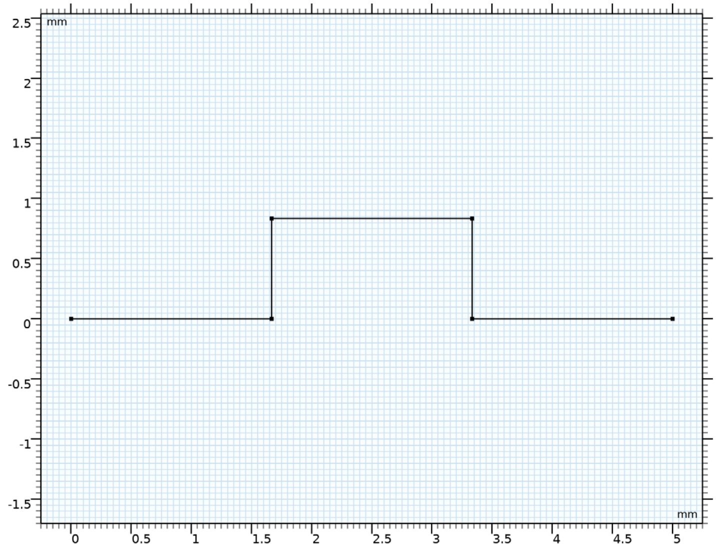
2 From the **Type** list, choose **Open curve**.

3 Locate the **Coordinates** section. From the **Data source** list, choose **Vectors**.

4 In the **x** text field, type `0 ul ul ul ul ul*2 ul*2 ul*2 ul*2 ul*3`.

5 In the **y** text field, type `0 0 0 ul/2 ul/2 ul/2 ul/2 0 0 0`.

6 Click **Build Selected**.



CROSSOVER

1 Right-click **Geometry Parts** and choose **2D Part**.

2 In the **Settings** window for **Part**, type `Crossover` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 In the **x** text field, type `ul*3`.

Line Segment 2 (ls2)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 Locate the **Starting Point** section. In the **y** text field, type `ul`.

6 Locate the **Endpoint** section. In the **x** text field, type `ul*3`.

7 In the **y** text field, type `ul`.

Line Segment 3 (ls3)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

5 Locate the **Starting Point** section. In the **x** text field, type `ul/2`.

6 Locate the **Endpoint** section. In the **x** text field, type `ul/2`.

7 In the **y** text field, type `ul`.

Array 1 (arr1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

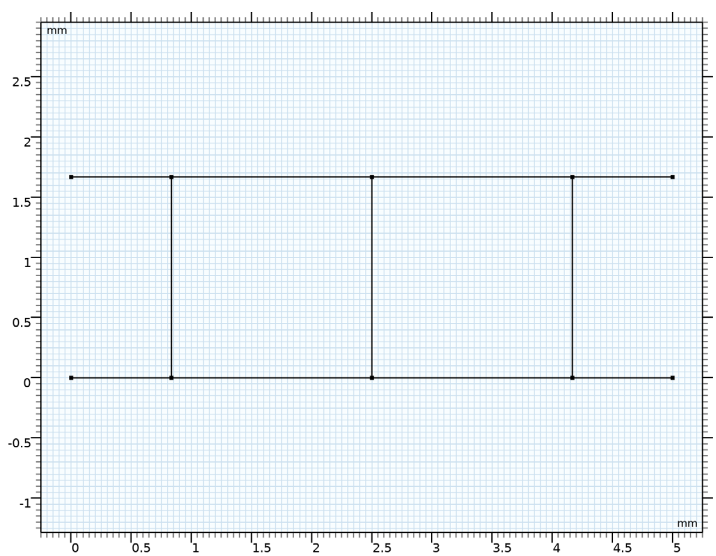
2 Select the object **ls3** only.

3 In the **Settings** window for **Array**, locate the **Size** section.

4 In the **x size** text field, type `3`.

5 Locate the **Displacement** section. In the **x** text field, type `ul`.

6 Click **Build Selected**.



FRONT-END, OUTER

1 Right-click **Geometry Parts** and choose **2D Part**.

2 In the **Settings** window for **Part**, type `Front-end, outer` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

Polygon 1 (pol1)

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

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

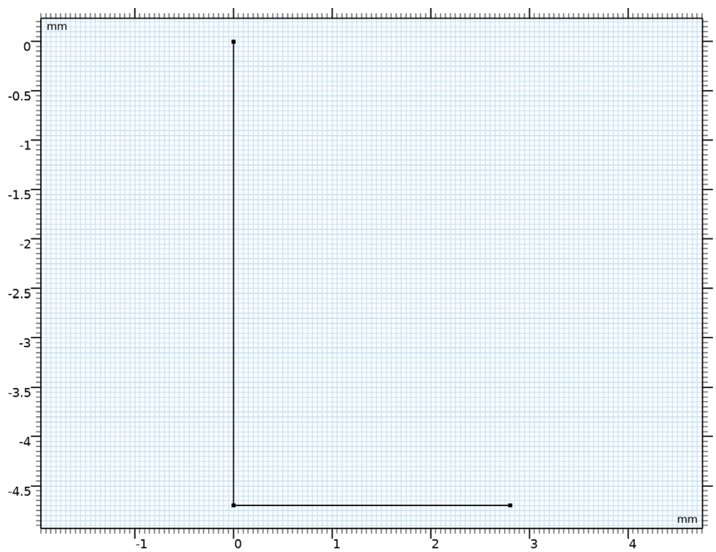
3 From the **Type** list, choose **Open curve**.

4 Locate the **Coordinates** section. From the **Data source** list, choose **Vectors**.

5 In the **x** text field, type `0 0 0 -1.5*array_d+ul*6`.

6 In the **y** text field, type `0 -1.5*(array_d-ul) -1.5*(array_d-ul) -1.5*(array_d-ul)`.

7 Click **Build Selected**.



FRONT-END, INNER

1 Right-click **Geometry Parts** and choose **2D Part**.

2 In the **Settings** window for **Part**, type `Front-end, inner` in the **Label** text field.

3 Locate the **Units** section. From the **Length unit** list, choose **mm**.

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

1 In the **Settings** window for **Polygon**, locate the **Object Type** section.

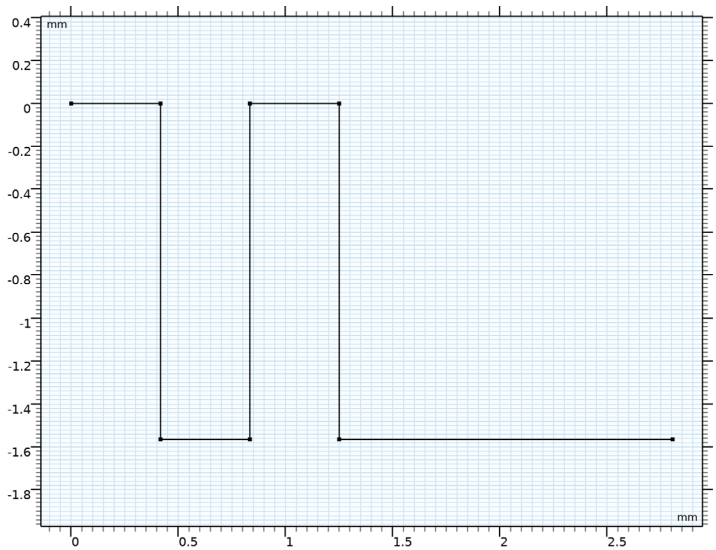
2 From the **Type** list, choose **Open curve**.

3 Locate the **Coordinates** section. From the **Data source** list, choose **Vectors**.

4 In the **x** text field, type `0 ul*0.25 ul*0.25 ul*0.25 ul*0.25 ul*0.5 ul*0.5 ul*0.5 ul*0.5 ul*0.75 ul*0.75 ul*0.75 ul*0.75 -1.5*array_d+ul*6`.

5 In the **y** text field, type `0 0 0 -(array_d-ul)/2 -(array_d-ul)/2 -(array_d-ul)/2 -(array_d-ul)/2 0 0 0 0 -(array_d-ul)/2 -(array_d-ul)/2 -(array_d-ul)/2`.

6 Click **Build Selected**.



GEOMETRY 1

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

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

90 Degree Hybrid 1 (pi1)

In the **Geometry** toolbar, click **Part Instance** and choose **90 Degree Hybrid**.

90 Degree Hybrid 2 (pi2)

1 In the **Geometry** toolbar, click **Part Instance** and choose **90 Degree Hybrid**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*5`.

4 Click **Build Selected**.

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

45 Degree Delay 1 (pi3)

1 In the **Geometry** toolbar, click **Part Instance** and choose **45 Degree Delay**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*2`.

Transition 1 (pi4)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Transition**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*7`.

4 Click **Build Selected**.

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

Front-end, outer 1 (pi5)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Front-end, outer**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*10`.

4 Click **Build Selected**.

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

Front-end, inner 1 (pi6)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Front-end, inner**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*10`.

4 In the **y-displacement** text field, type `ul`.

5 Click **Build Selected**.

Mirror 1 (mir1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Mirror**.

2 Click the **Select All** button in the **Graphics** toolbar.

3 In the **Settings** window for **Mirror**, locate the **Input** section.

4 Select the **Keep input objects** check box.

5 Locate the **Point on Line of Reflection** section. In the **y** text field, type `ul*1.5`.

6 Locate the **Normal Vector to Line of Reflection** section. In the **x** text field, type `0`.

7 In the **y** text field, type `1`.

8 Click **Build Selected**.

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

Crossover 1 (pi7)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Crossover**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*2`.

4 In the **y-displacement** text field, type `ul`.

Crossover 2 (pi8)

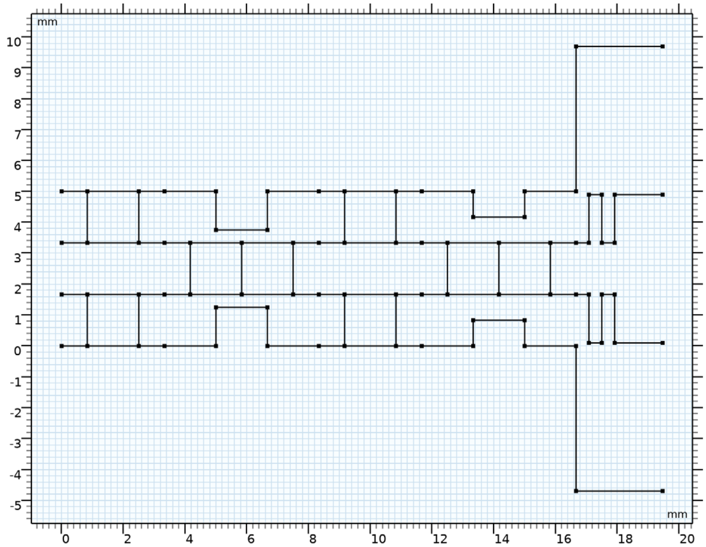
1 In the **Geometry** toolbar, click **Part Instance** and choose **Crossover**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 In the **x-displacement** text field, type `ul*7`.

4 In the **y-displacement** text field, type `ul`.

5 Click **Build All Objects**.



TRANSMISSION LINE (TL)

Transmission Line Equation 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Transmission Line (tl)** click **Transmission Line Equation 1**.

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

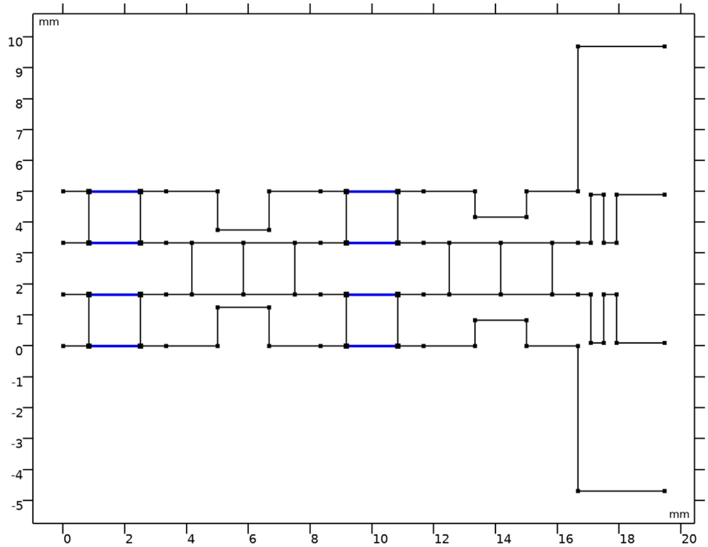
3 In the L text field, type `L0`.

4 In the C text field, type `C0`.

Transmission Line Equation 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Transmission Line Equation**.

2 Select Boundaries 6, 7, 9, 10, 43, 44, 46, and 47 only.



Set the impedance of the selected transmission lines (branch-lines in the 90 degree hybrid) to `Z0/sqrt(2)` by adjusting the distributed inductance and capacitance values.

3 In the **Settings** window for **Transmission Line Equation**, locate the **Transmission Line Equation** section.

4 In the L text field, type `L0*z1`.

5 In the C text field, type `C0/z1`.

Lumped Port 1

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

2 Select Point 4 only.

See Figure 8 to confirm the lumped port configuration.

Lumped Port 2

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

2 Select Point 3 only.

Lumped Port 3

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

2 Select Point 2 only.

Lumped Port 4

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

2 Select Point 1 only.

Lumped Port 5

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

2 Select Point 82 only.

Lumped Port 6

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

2 Select Point 81 only.

Lumped Port 7

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

2 Select Point 80 only.

Lumped Port 8

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

2 Select Point 79 only.

3 In the **Model Builder** window, click **Transmission Line (tl)**.

4 In the **Settings** window for **Transmission Line**, locate the **Port Sweep Settings** section.

5 Select the **Use manual port sweep** check box.

6 Click **Configure Sweep Settings**. By clicking the **Configure Sweep Settings** button, all necessary port sweep settings such as sweep parameter and parametric study step will be automatically added.

MESH 1

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

Size

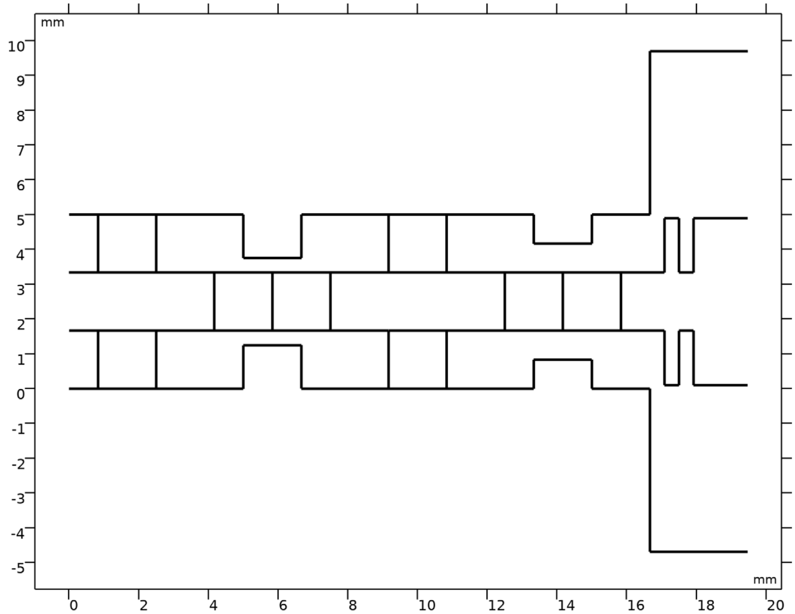
1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.

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 `ul/15`.

5 Click **Build All**.



STUDY 1

1. In the **Model Builder** window, click **Study 1**.
2. In the **Settings** window for **Study**, locate the **Study Settings** section.
3. Clear the **Generate default plots** check box.

Step 1: Frequency Domain

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

1. In the **Model Builder** window, click **Parametric Sweep 1**.
2. In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
PortName (Port name parameter for sweep)	1 2 3 4	

Sweep only four input ports.

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

RESULTS

2D Plot Group 1

In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

Line 1

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

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

3 In the **Expression** text field, type `20*log10(abs(V))`.

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

Other input ports (port 1, port2 and port 3) are fully isolated from the excited port 4. See Figure 9.

5 Click to expand the **Range** section. Select the **Manual color range** check box.

6 In the **Minimum** text field, type `-10`.

7 In the **Maximum** text field, type `0`.

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

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

Figure 10 shows that the input power to port 4 is equally split into all output ports (-6 dB).

Global Evaluation 1

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

2 In the **Settings** window for **Global Evaluation**, locate the **Expressions** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`arg(tl.Vport_5)`	`deg`	`Port 5 phase`
`arg(tl.Vport_6)`	`deg`	`Port 6 phase`

Expression	Unit	Description
arg(tl.Vport_7)	deg	Port 7 phase
arg(tl.Vport_8)	deg	Port 8 phase

4 Click **Evaluate**.

TABLE 1

1 Go to the **Table 1** window.

Compare the evaluated values to those in Table 3.