

**RF PCB Toolbox™**

Getting Started



**MATLAB®**

R2021b



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*RF PCB Toolbox™ Getting Started Guide*

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# Getting Started with RF PCB Toolbox

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## **RF PCB Toolbox Product Description**

### **Perform electromagnetic analysis of printed circuit boards**

RF PCB Toolbox™ provides functions and apps for designing, analyzing, and visualizing high-speed and RF multi-layer printed circuit boards (PCBs). You can design components with parameterized or arbitrary geometry, including distributed passive structures such as traces, bends, and vias. Using the frequency-domain method of moments (MoM) and other EM techniques, you can model coupling, dispersion, and parasitic effects.

With RF PCB Toolbox, designers of RF boards, modules, MMICs, and SiPs can predict PCB performance and verify that the manufactured PCB meets specifications. For RF and antenna designers, the toolbox provides parameterized models of distributed filters, couplers, splitters, matching networks, and Gerber file generation. Toolbox support for ODB++ and databases from Cadence® Allegro®, Mentor Expedition, Altium®, and Zuken enables signal integrity engineers to analyze the high-speed portions of the PCB layout.

# RF PCB Tutorials

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- “Rat-Race Coupler - Visualize and Analyze” on page 2-2
- “Filter Coupled Line - Visualize and Analyze” on page 2-7
- “Interdigital Capacitor - Visualize and Analyze” on page 2-12
- “Spiral Inductor - Visualize and Analyze” on page 2-16
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## Rat-Race Coupler - Visualize and Analyze

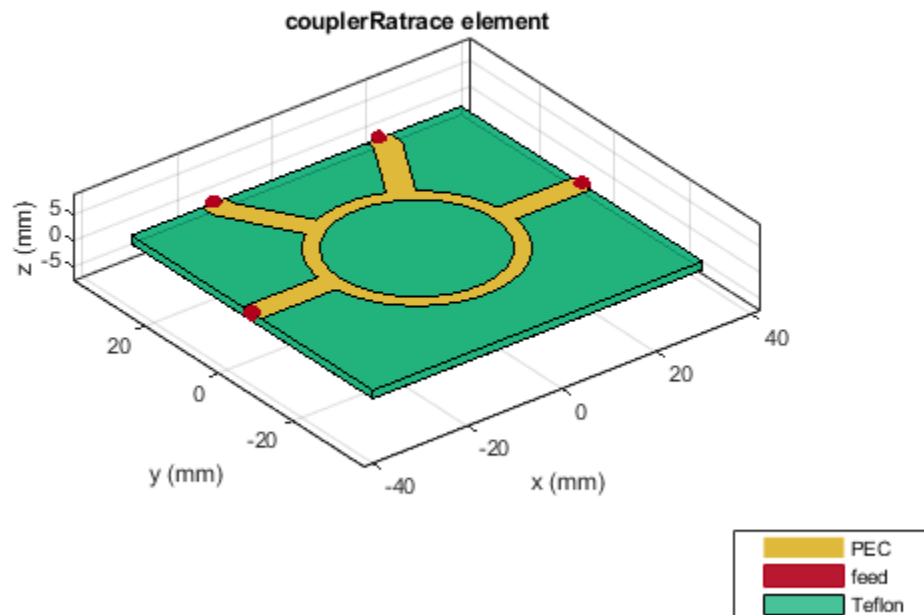
This example shows you how to create, visualize, and analyze a Rat-Race Coupler.

Create a rat-race coupler with default properties.

```
ratrace = couplerRatrace  
  
ratrace =  
  couplerRatrace with properties:  
  
    PortLineLength: 0.0186  
    PortLineWidth: 0.0050  
    CouplerLineWidth: 0.0030  
    Circumference: 0.1110  
    Height: 0.0016  
    Substrate: [1x1 dielectric]  
    Conductor: [1x1 metal]
```

View the coupler.

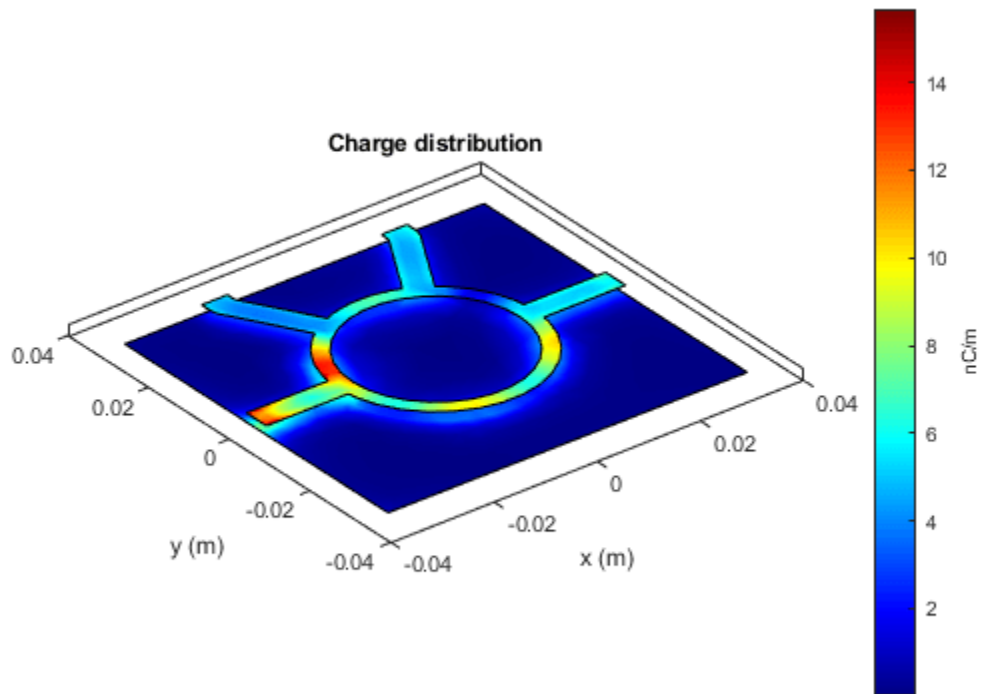
```
show(ratrace)
```



Plot the charge distribution at 5 GHz.

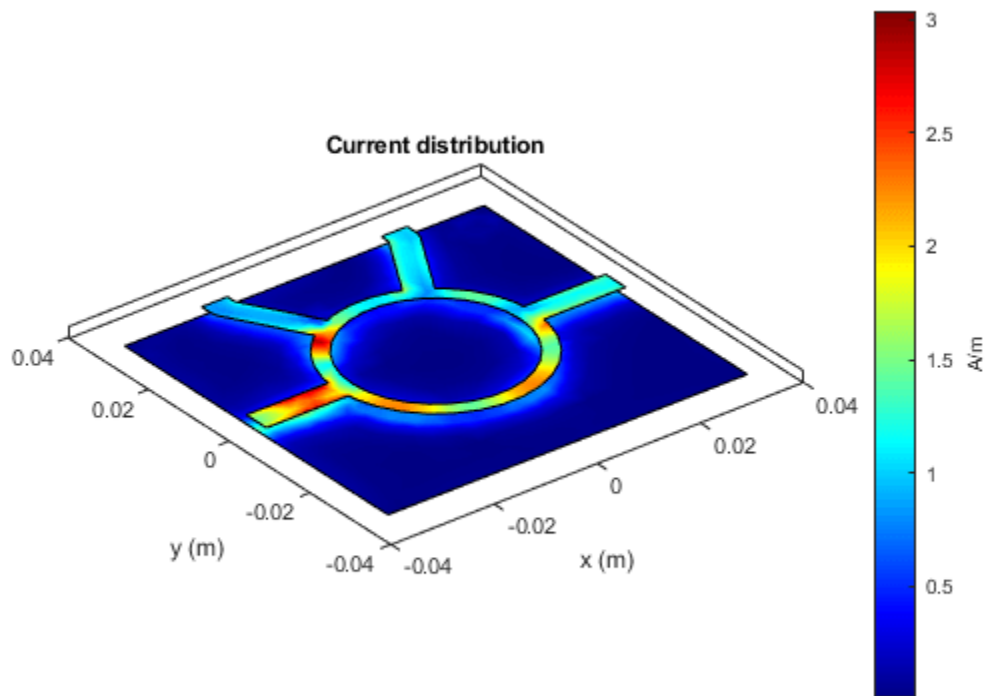
```
charge(ratrace, 5e9)
```





Plot the current distribution at 5 GHz.

```
figure  
current(ratrace, 5e9)
```



Calculate and plot the s-parameters.

```
spar = sparameters(ratrace,linspace(1e9,5e9,20))
```

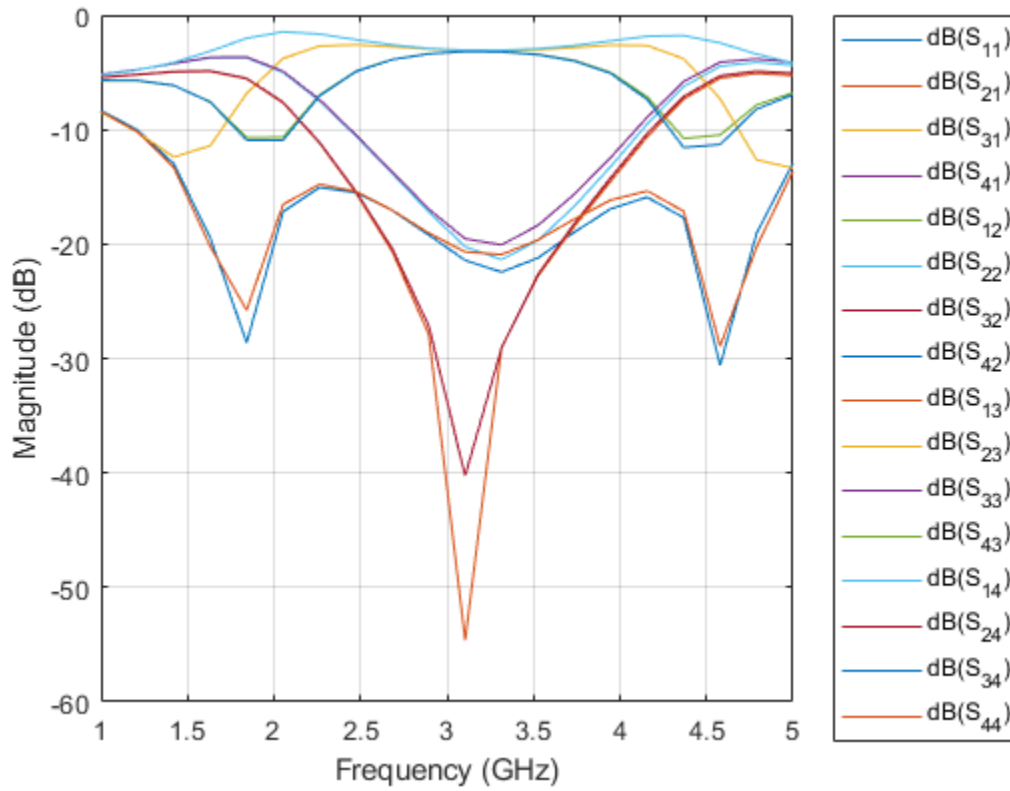
```
spar =  
  sparameters: S-parameters object
```

```
    NumPorts: 4  
    Frequencies: [20x1 double]  
    Parameters: [4x4x20 double]  
    Impedance: 50
```

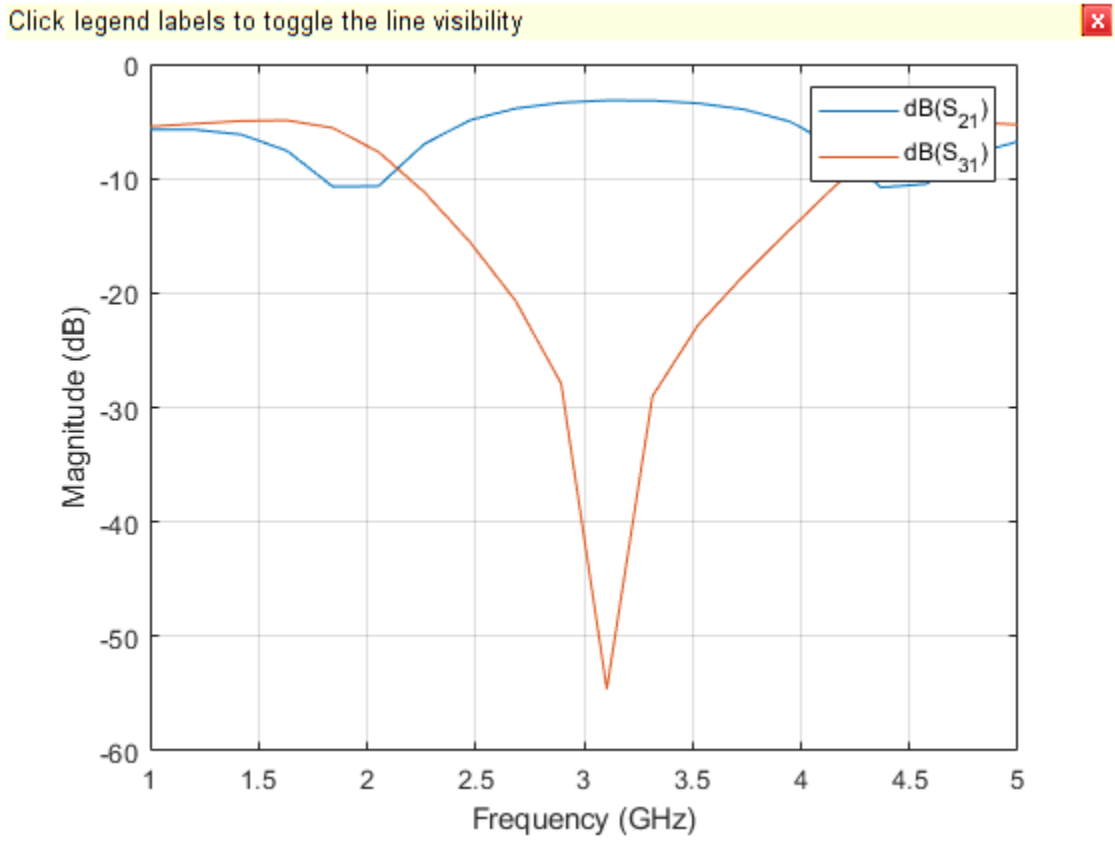
```
rfparam(obj,i,j) returns S-parameter  $S_{ij}$ 
```

```
rfplot(spar)
```

Click legend labels to toggle the line visibility



```
figure
rfplot(spar,2,1)
hold on
rfplot(spar,3,1)
hold off
```



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## Filter Coupled Line - Visualize and Analyze

This example shows you how to create, visualize, and analyze a coupled line filter.

Create a coupled line filter with default properties.

```
filter = filterCoupledLine
```

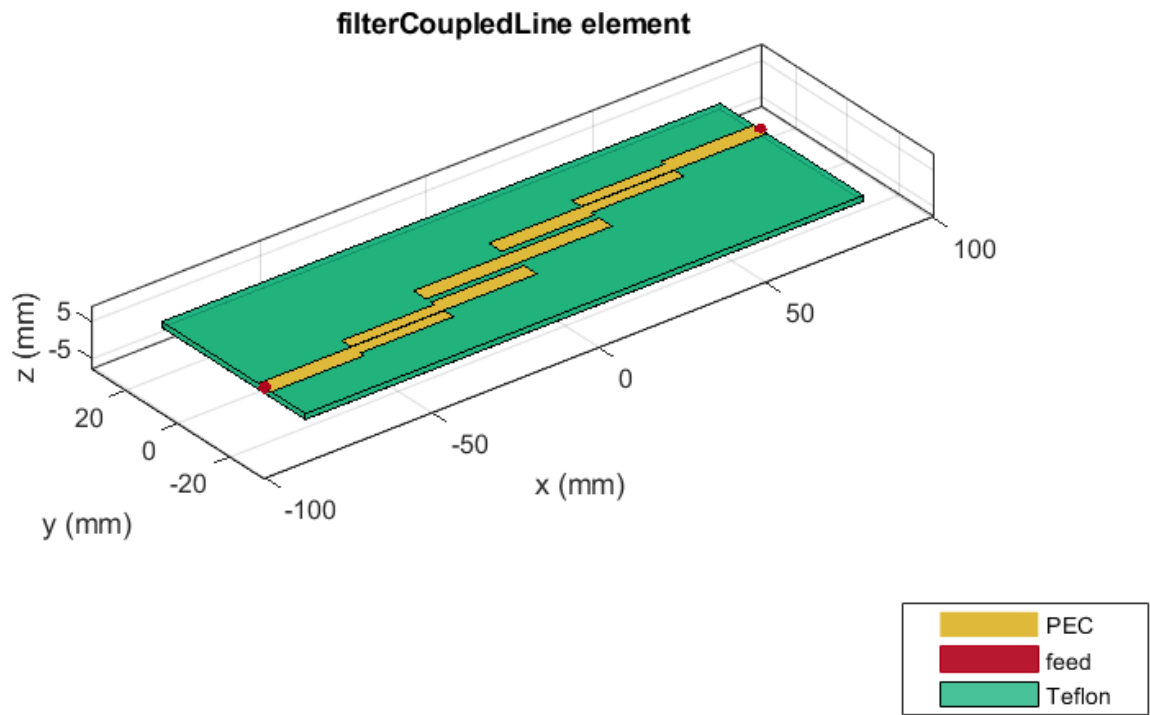
```
filter =
```

```
  filterCoupledLine with properties:
```

```
    FilterOrder: 3
    PortLineLength: 0.0279
    PortLineWidth: 0.0051
    CoupledLineLength: [0.0279 0.0279 0.0279 0.0279]
    CoupledLineWidth: [0.0036 0.0049 0.0049 0.0036]
    CoupledLineSpacing: [1.8270e-04 0.0019 0.0019 1.8270e-04]
    Height: 0.0016
    GroundPlaneWidth: 0.0551
    Substrate: [1x1 dielectric]
    Conductor: [1x1 metal]
```

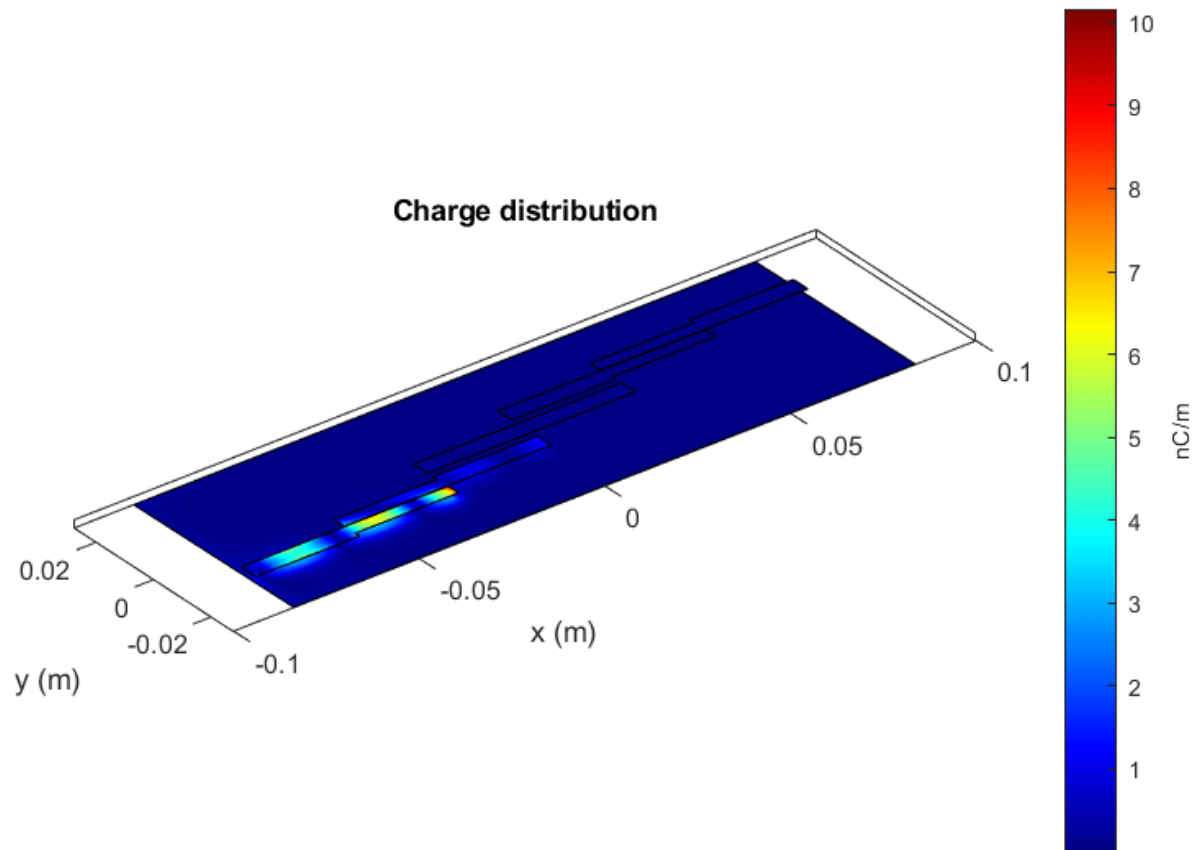
View the filter.

```
show(filter)
```



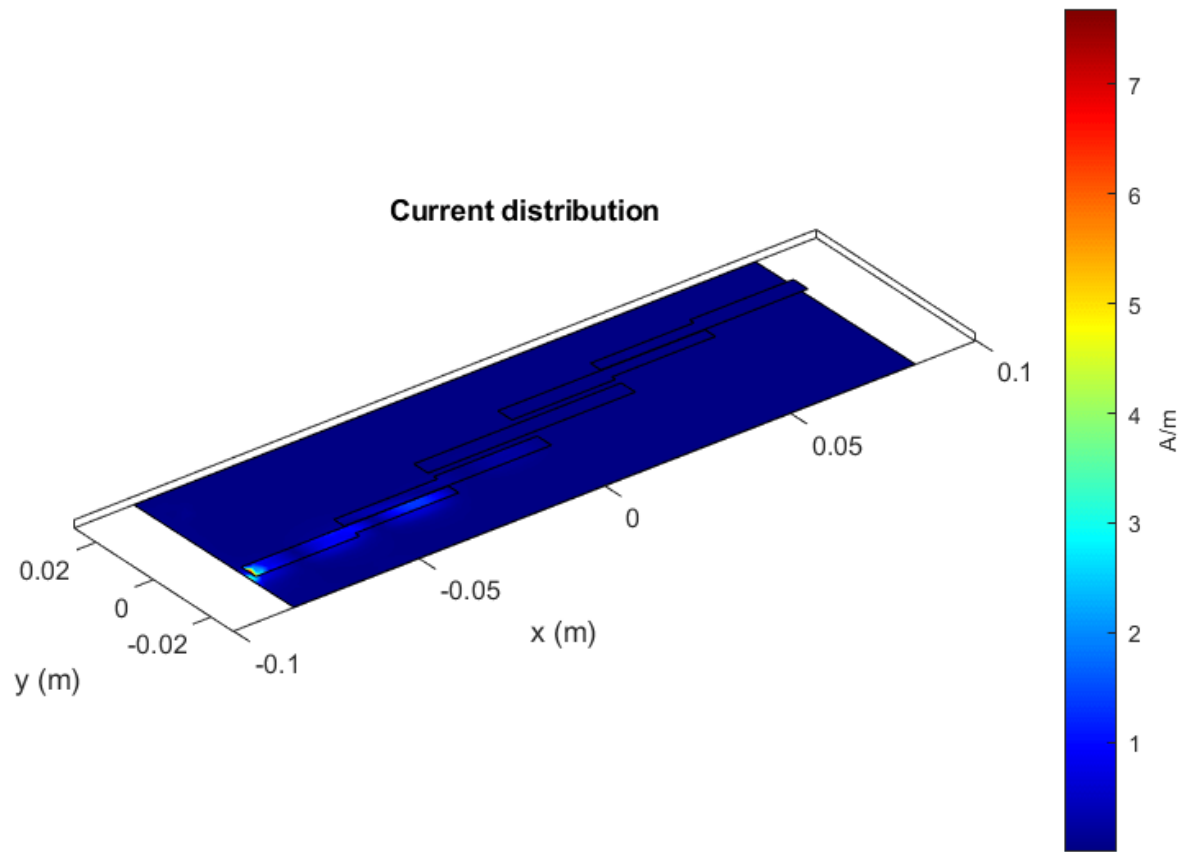
Plot the charge distribution at 5 GHz.

```
charge(filter, 5e9)
```



Plot the current distribution at 5 GHz.

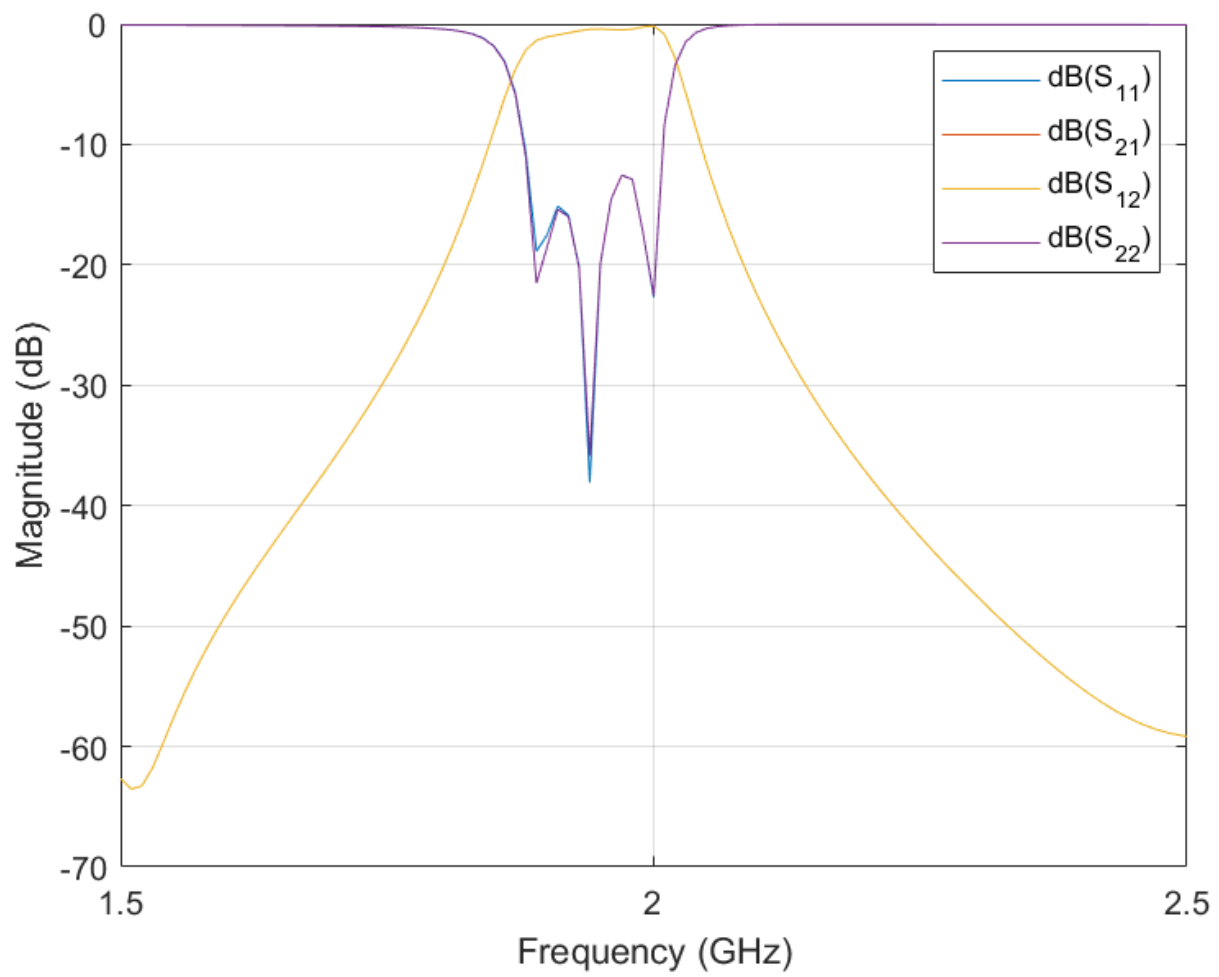
```
figure  
current(filter, 5e9)
```



Calculate and plot the s-parameters.

```
spar = sparameters(filter,linspace(1.5e9,2.5e9,101));  
figure,rfplot(spar)
```





## Interdigital Capacitor - Visualize and Analyze

This example shows you how to create, visualize, and analyze an interdigital capacitor.

Create an interdigital capacitor with default properties.

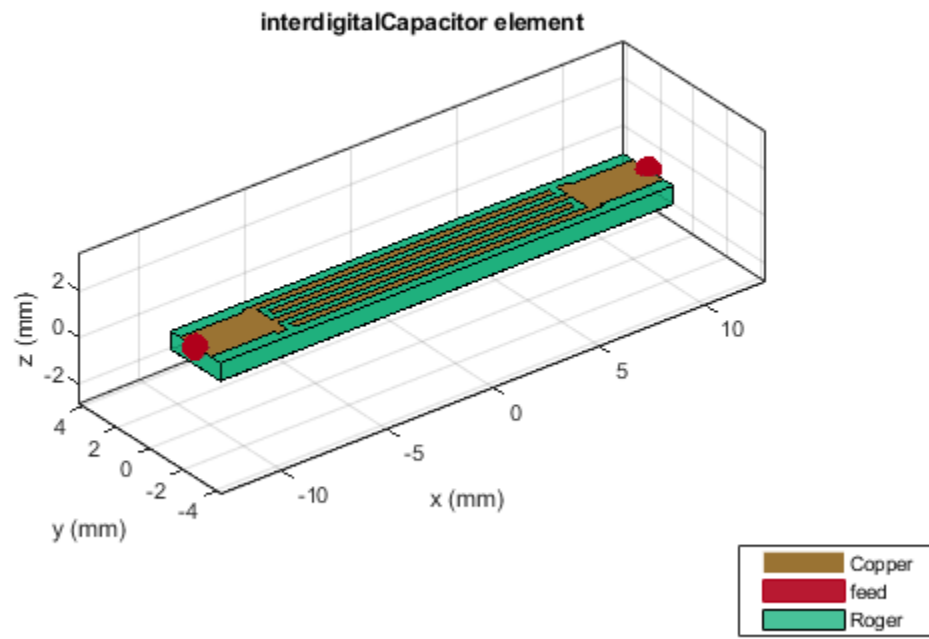
```
capacitor = interdigitalCapacitor
```

```
capacitor =  
    interdigitalCapacitor with properties:
```

```
        NumFingers: 4  
        FingerLength: 0.0137  
        FingerWidth: 3.1600e-04  
        FingerSpacing: 3.0000e-04  
        FingerEdgeGap: 3.4100e-04  
        TerminalStripWidth: 5.0000e-04  
        PortLineWidth: 0.0019  
        PortLineLength: 0.0030  
        Height: 7.8700e-04  
        GroundPlaneWidth: 0.0030  
        Substrate: [1x1 dielectric]  
        Conductor: [1x1 metal]
```

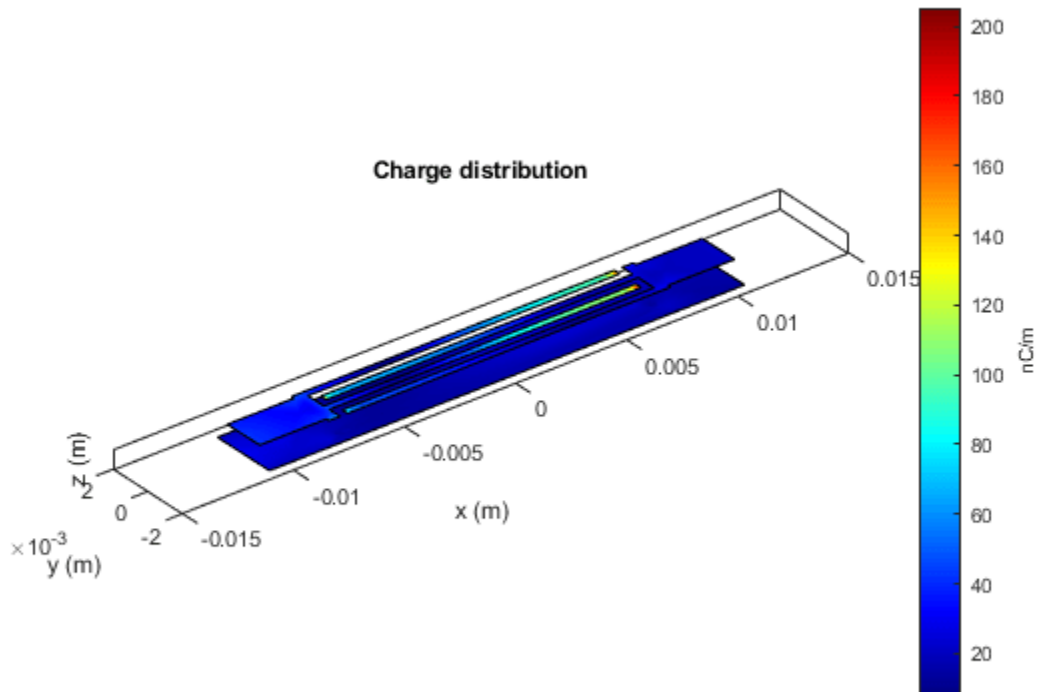
View the capacitor.

```
show(capacitor)
```



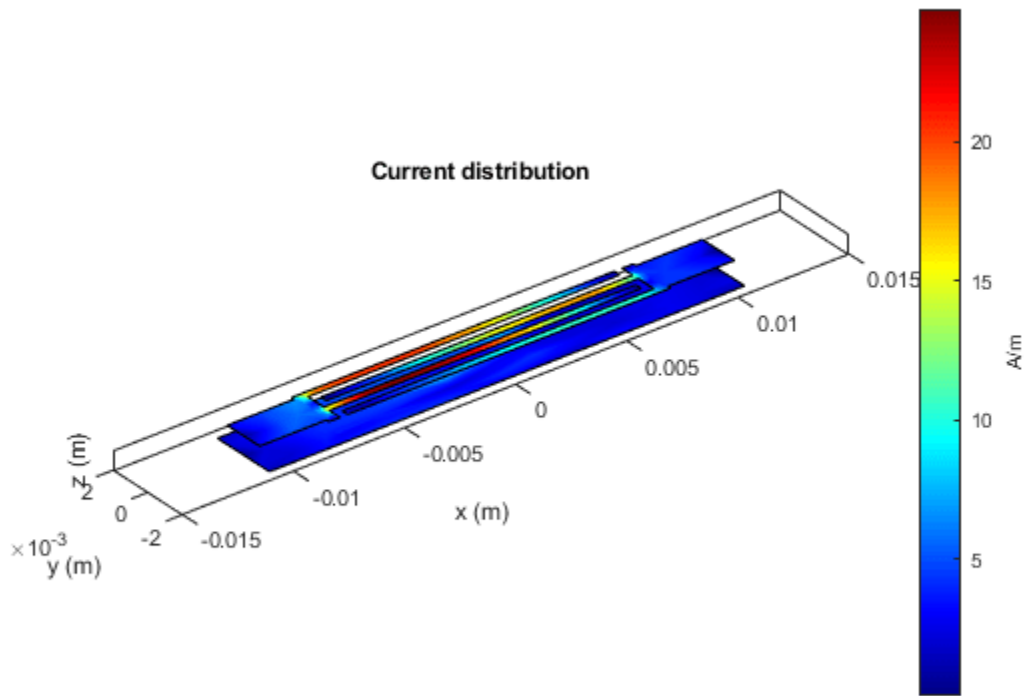
Plot the charge distribution at 5 GHz.

```
charge(capacitor, 5e9)
```



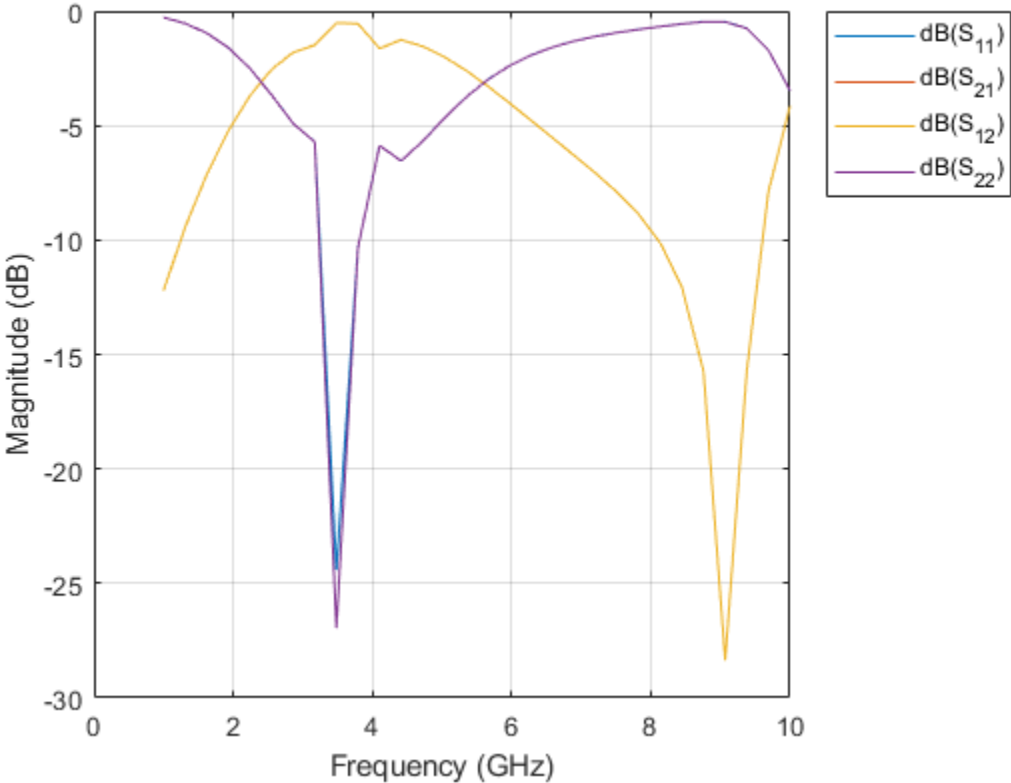
Plot the current distribution at 5 GHz.

```
figure  
current(capacitor, 5e9)
```



Calculate and plot the s-parameters.

```
spar = sparameters(capacitor, linspace(1e9, 10e9, 30));  
rfplot(spar)
```



## Spiral Inductor - Visualize and Analyze

This example shows you how to create, visualize, and analyze a spiral inductor.

Create a spiral inductor with default properties.

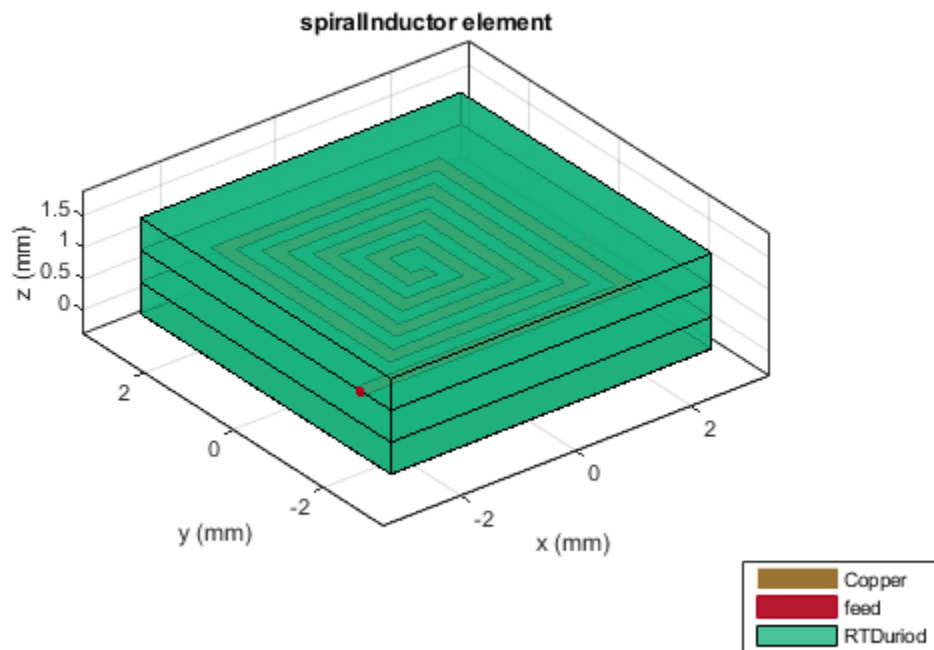
```
inductor = spiralInductor

inductor =
    spiralInductor with properties:

        SpiralShape: 'Square'
        InnerDiameter: 5.0000e-04
        Width: 2.5000e-04
        Spacing: 2.5000e-04
        NumTurns: 4
        Height: 0.0010
        GroundPlaneLength: 0.0056
        GroundPlaneWidth: 0.0056
        Substrate: [1x1 dielectric]
        Conductor: [1x1 metal]
```

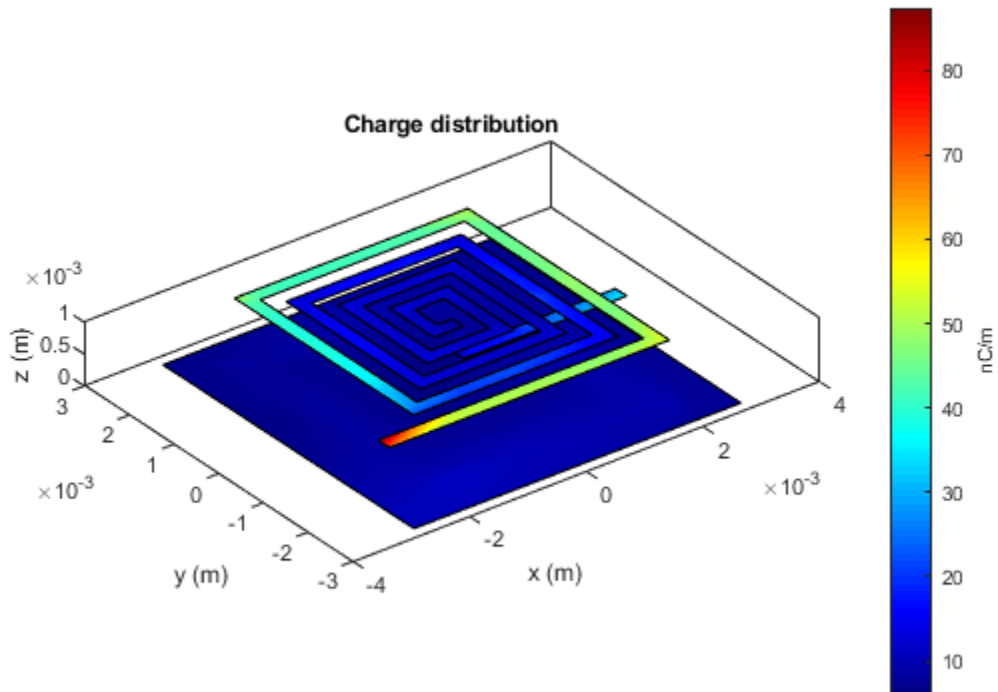
View the inductor.

```
show(inductor)
```



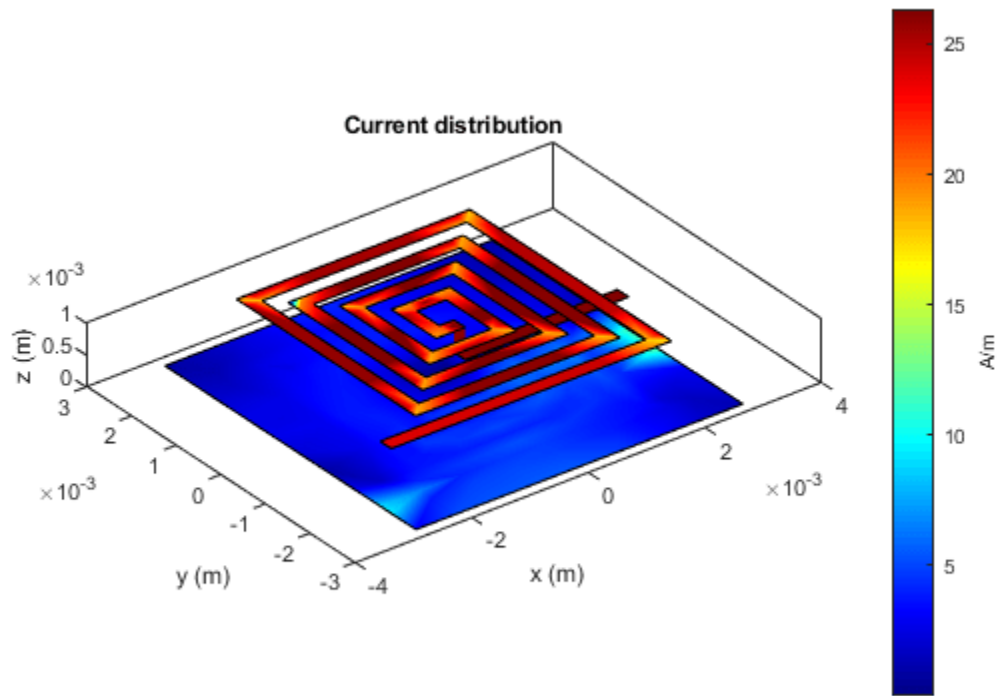
Plot the charge distribution at 500 MHz.

```
charge(inductor, 500e6)
```



Plot the current distribution at 500 MHz.

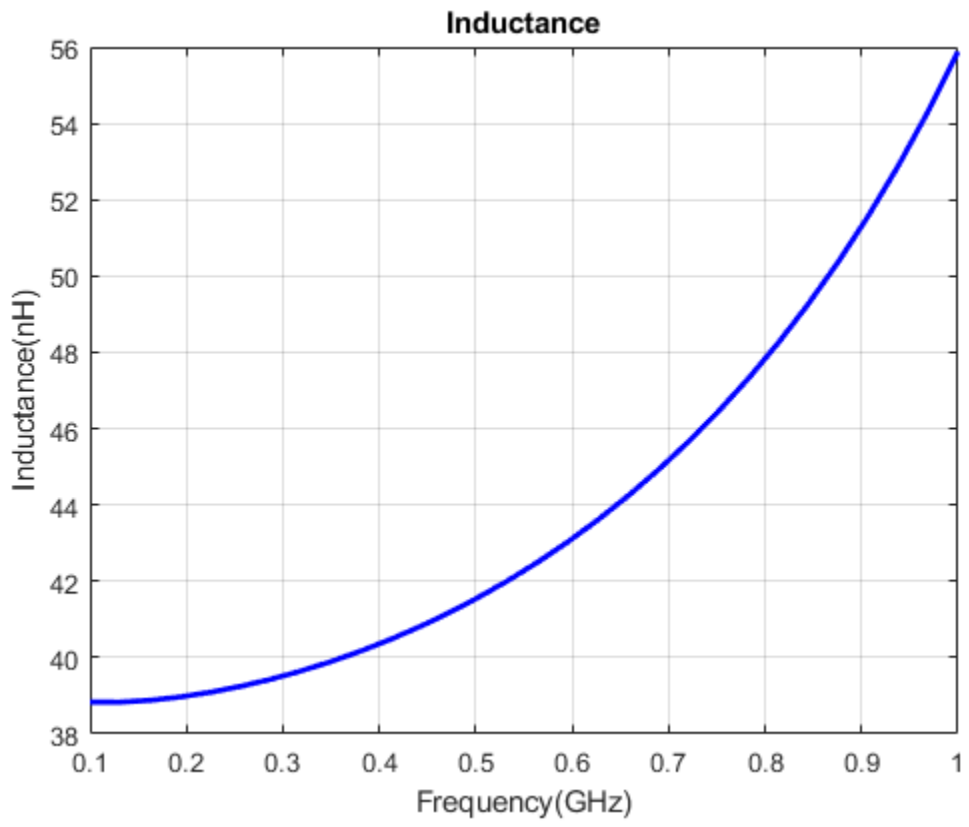
```
figure  
current(inductor, 500e6)
```



Calculate and plot the inductance.

```
figure;
inductance(inductor, linspace(100e6, 1e9, 30));
```





## Shunt Radial Stub - Visualize and Analyze

This example shows you how to create, visualize, and analyze a radial stub shunt on the X-Y plane.

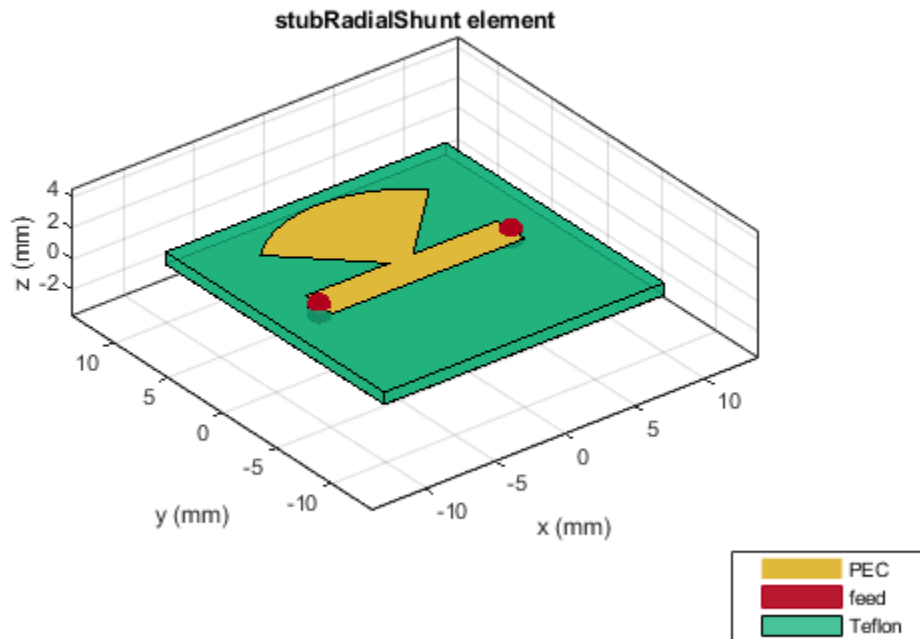
Create a shunt radial stub with default properties.

```
stub = stubRadialShunt
```

```
stub =  
  stubRadialShunt with properties:  
  
    StubType: 'Single'  
   OuterRadius: 0.0085  
   InnerRadius: 0.0012  
      Angle: 90  
  PortLineLength: 0.0137  
  PortLineWidth: 0.0025  
      Height: 8.0000e-04  
GroundPlaneLength: 0.0200  
GroundPlaneWidth: 0.0200  
   Substrate: [1x1 dielectric]  
  Conductor: [1x1 metal]
```

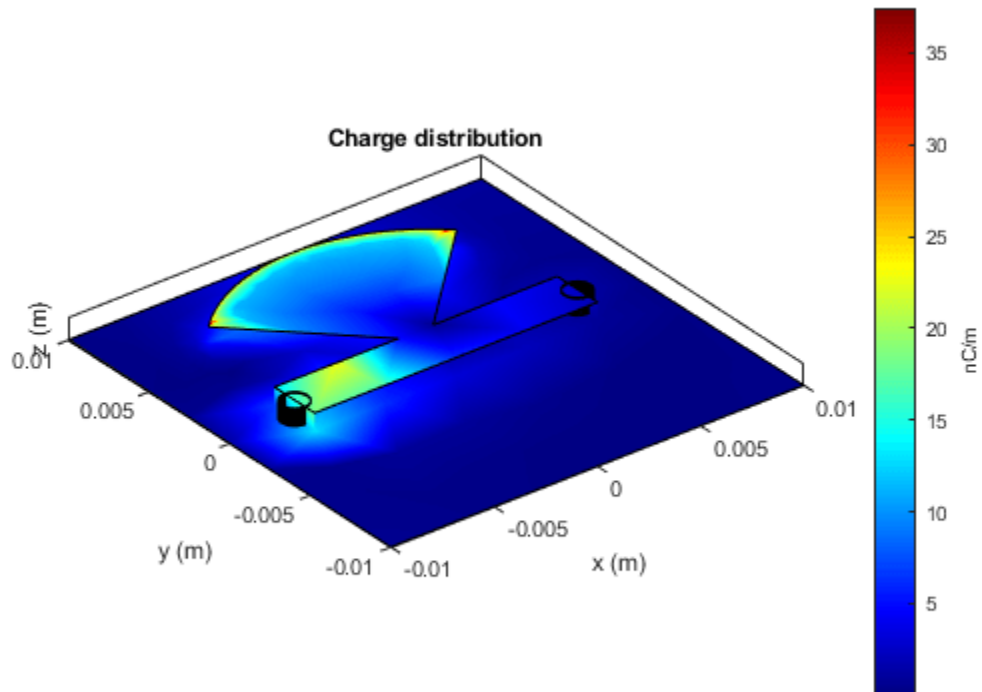
View the stub.

```
show(stub)
```



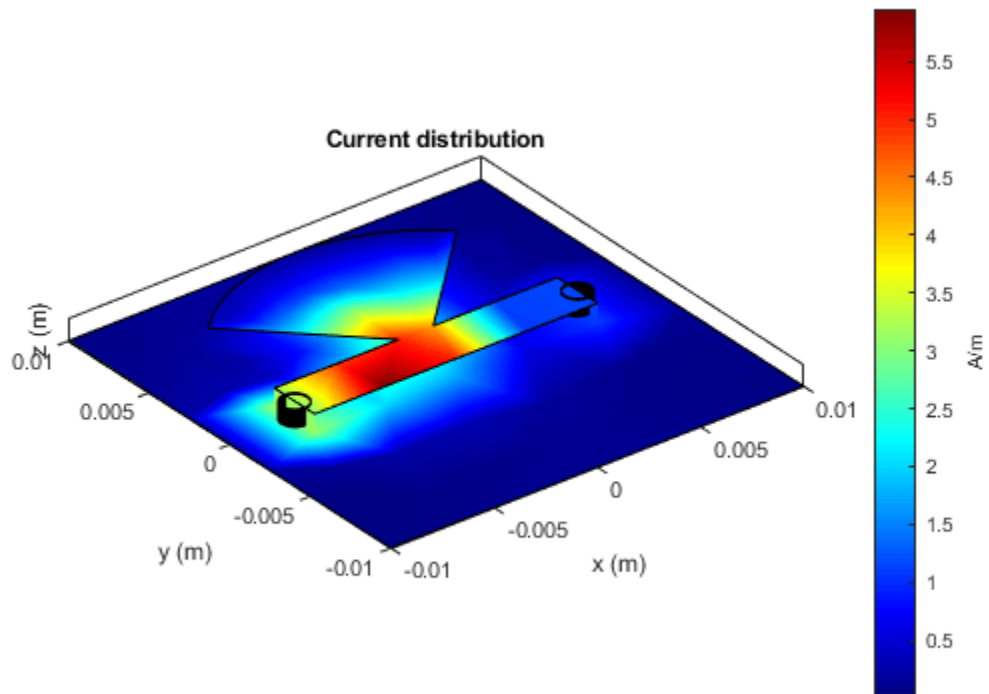
Plot the charge distribution at 5 GHz.

```
charge(stub, 5e9)
```



Plot the current distribution at 5 GHz.

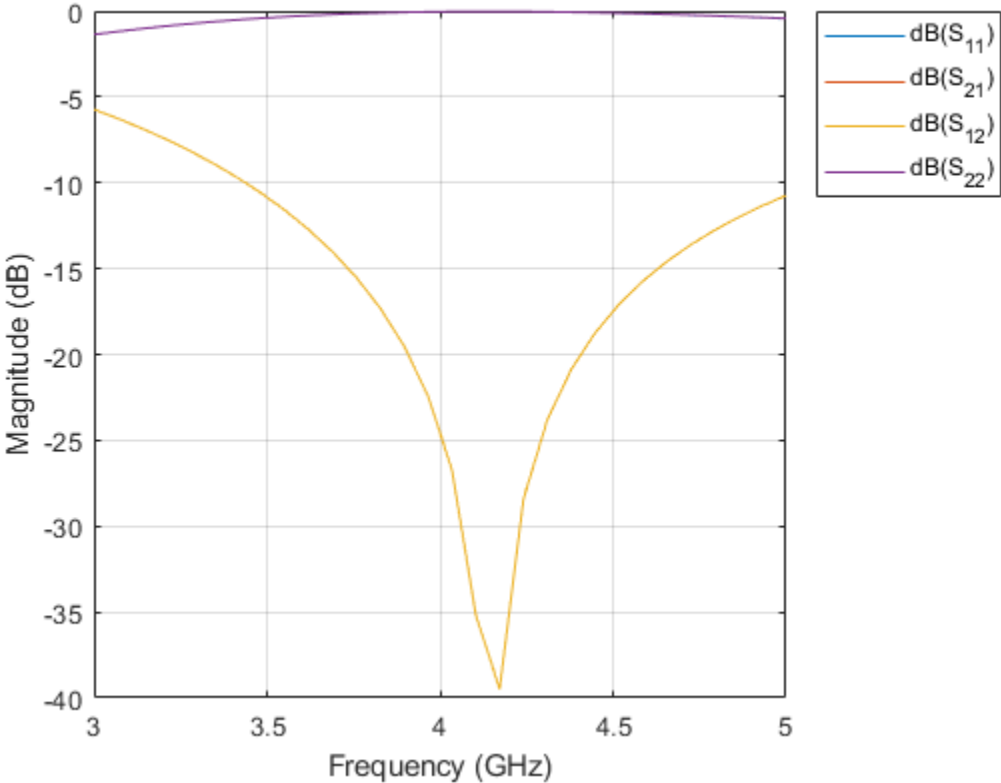
```
figure  
current(stub, 5e9)
```



Calculate and plot the s-parameters.

```
spar = sparameters(stub, linspace(3e9, 5e9, 30));  
rfplot(spar)
```

Click legend labels to toggle the line visibility ✖





# RF PCB Concepts

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- “Characteristic Impedance of Transmission Lines” on page 3-2
- “Scattering Parameters or S-Parameters” on page 3-4
- “Behavioral Models” on page 3-12

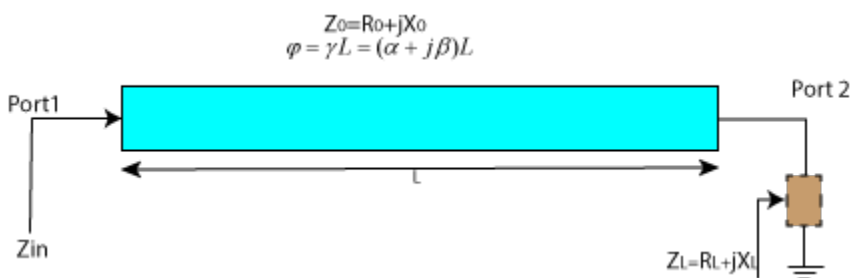
## Characteristic Impedance of Transmission Lines

### Characteristic Impedance

Consider an ideal, infinitely long transmission line. Exciting the input of this transmission line with the alternating voltage  $V_{in}(t)$  results in the current  $I_{in}(t)$ . The characteristic impedance of this transmission line is given by the equation:

$$Z_0 = \frac{V_{in}(t)}{I_{in}(t)}$$

Consider a transmission line of length  $L$  terminated by load impedance of  $Z_L$ .



The complex propagation constant for this line is given by the equation:

$$\gamma = (\alpha + j\beta)$$

where  $\alpha$  and  $\beta$  are the attenuation and phase constants. The complex characteristic impedance is given by the equation:

$$Z_0 = R_0 + jX_0$$

where  $R_0$  and  $X_0$  are the real and imaginary parts, respectively.

The input impedance of the line is given by the equation in:

### Characteristic Impedances of Microstrip and Coplanar Waveguide Transmission Lines

Create microstrip and coplanar waveguide transmission lines with default properties. Use the `getZ0` from RF PCB Toolbox to calculate the characteristic impedance of following transmission lines:

- `microstripline`

```
mline = microstripline;
Z0 = getZ0(mline)
```

```
Z0 =
```

```
47.6145 - 0.0004i
```

- `coplanarWaveguide`

```
waveguide = coplanarWaveguide;
Z0 = getZ0(waveguide)
```



$Z_0 =$

$$47.8622 + 0.0041i$$

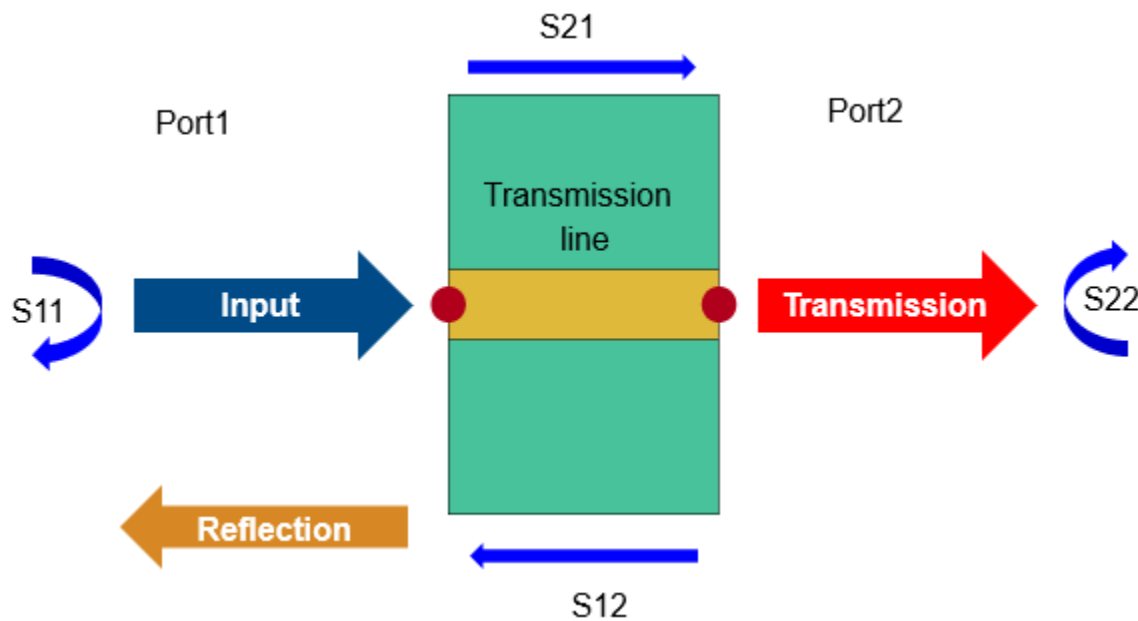
## Scattering Parameters or S-Parameters

The S-parameters or scattering parameters represent the linear characteristics of radio frequency (RF) printed circuit board (PCB) components. The parameter matrix describes the changes in the reflected and transmitted waves with respect to the incident wave at an N-port PCB component. Using S-parameters you can calculate the gain, loss, phase delay, voltage standing wave ratio (VSWR), and other characteristics of any PCB component or linear network. S-parameters can also be called the behavioral representation of a network.

### Basic Concepts

S-parameters are defined in terms of transmission and reflection coefficients. Consider a two-port transmission line. For a two-port device, there are four S-parameters:

- Reflected/Input =  $S_{11}$  and  $S_{22}$
- Transmitted/Input =  $S_{12}$  and  $S_{21}$



$S_{21}$  is the measure of the transmitted signal from port 2 relative to the input entering port 1.  $S_{11}$  is the measure of the reflected signal from port 1 relative to the input entering port 1.

For a multiport network, the transmission and reflection coefficients are defined as  $S_{nn}$ ,  $S_{mm}$ ,  $S_{nm}$ , and  $S_{mn}$ , where:

- $m$  is the number of input ports.
- $n$  is the number of output ports.

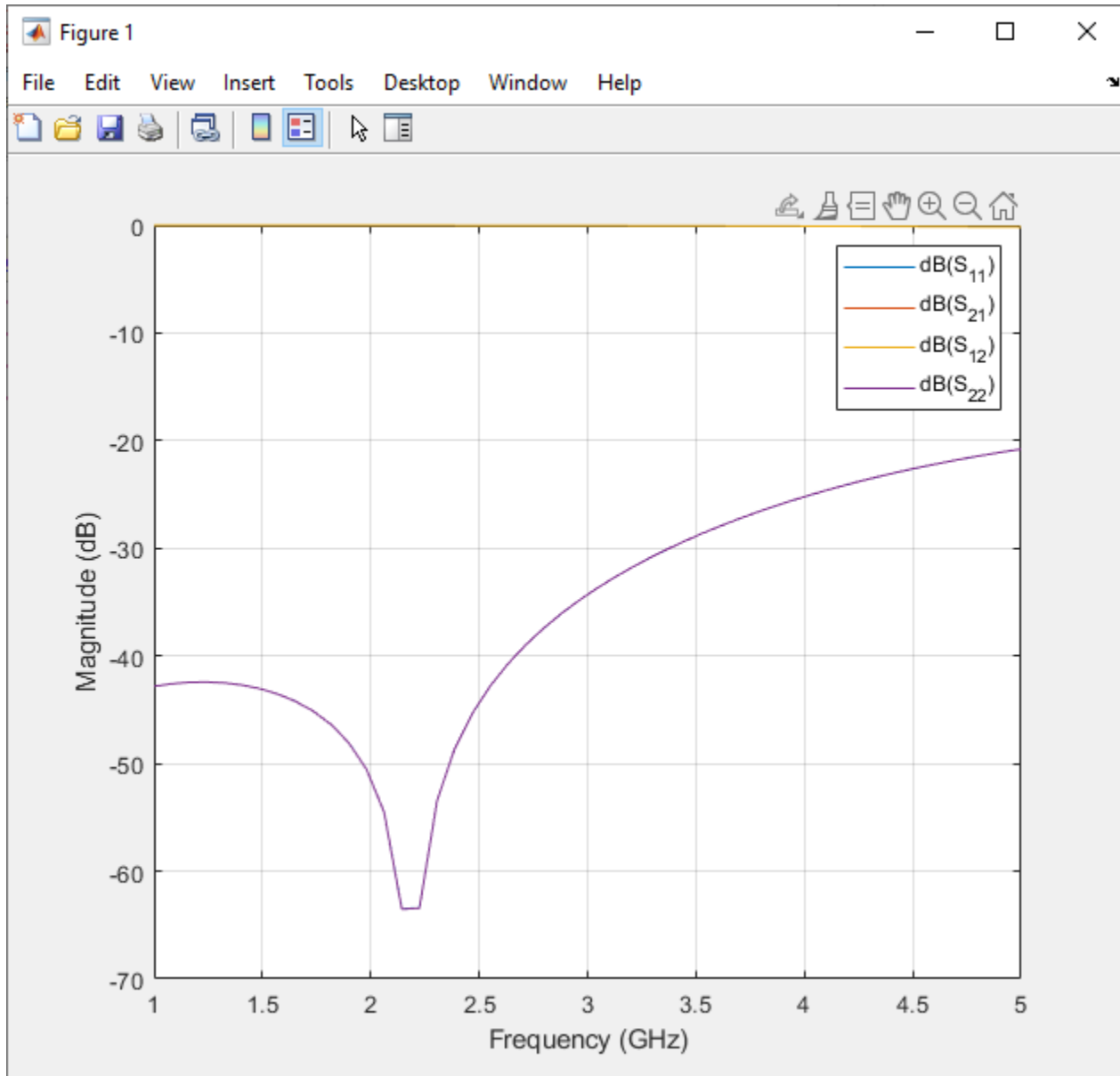
### Understanding S-Parameter Plots

#### S-Parameters of Microstrip Transmission Lines

Consider a microstrip transmission line from "Transmission Lines". The parameter values for this microstrip transmission line are for a frequency range of 1-5 GHz. Calculate and plot the S-

parameters at this frequency range. The operating frequency for the microstrip transmission line is around 2.5 GHz.

```
mline = microstripLine;
spar = sparameters(mline,linspace(1e9,539,50));
rfplot(spar)
```

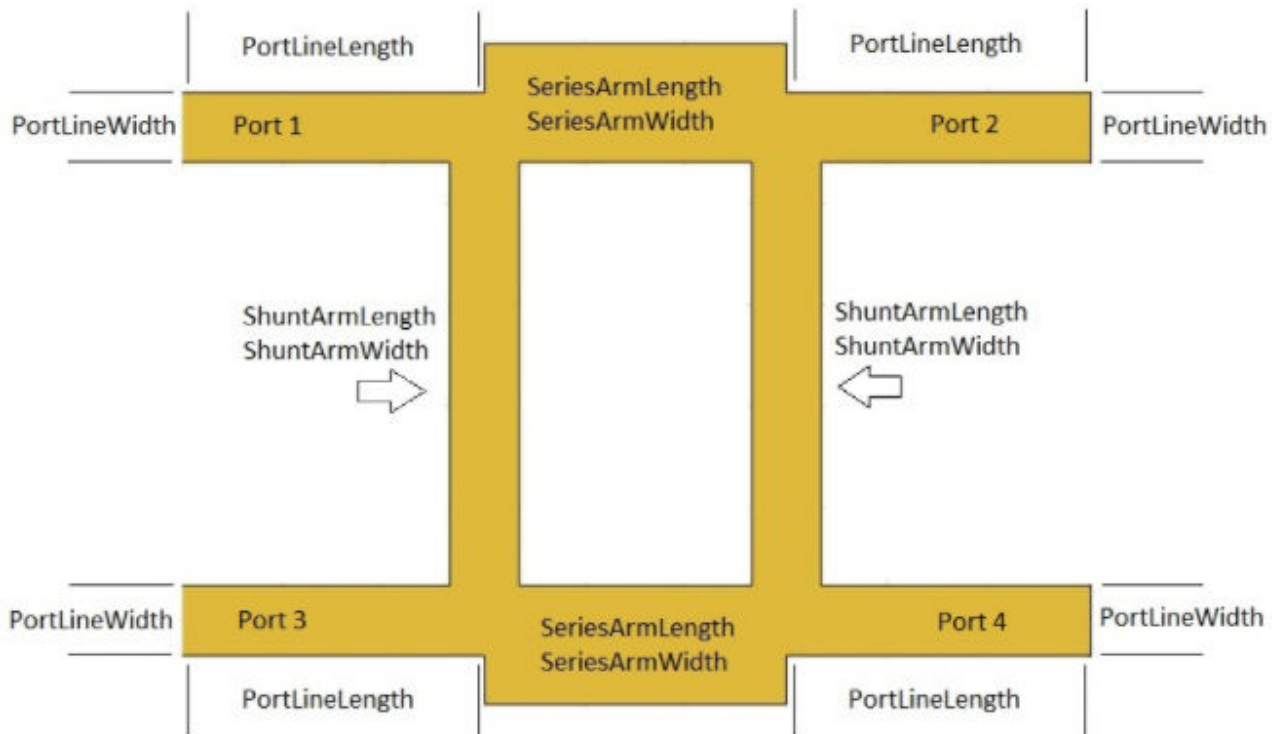


Let us look at the  $S_{11}$  and  $S_{21}$  of the plot.

- The  $S_{11}$  plot shows the return loss as almost negligible at -50 dB at around 2.3 GHz. As the frequency increases, more signal is reflected back to the input port.
- The  $S_{21}$  plot describes the end-to-end transmission of the signal. The plot is flat throughout at 0 dB showing very little loss at all frequencies.

### S-Parameters of Branchline Coupler

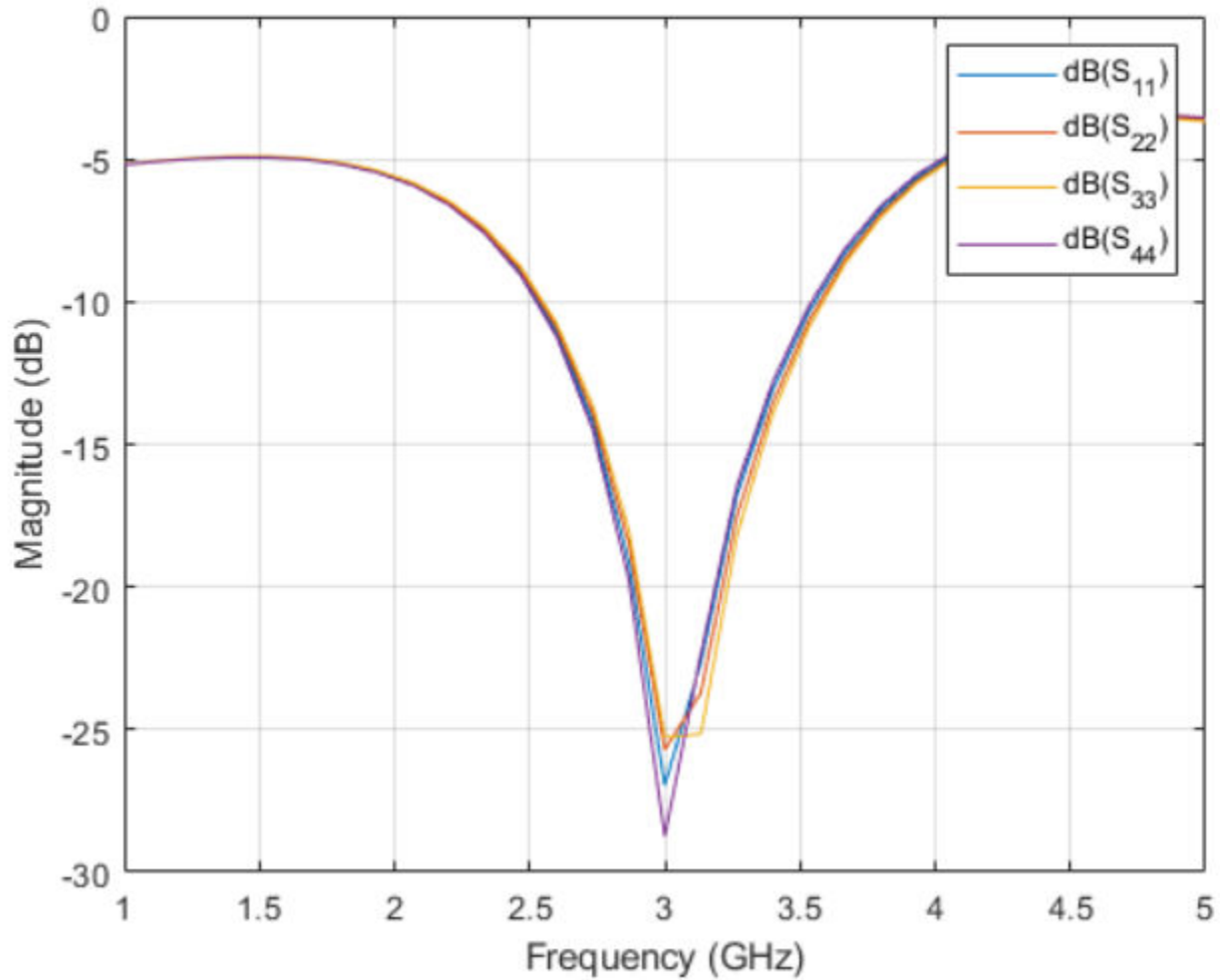
A branchline coupler is a four-Port coupler that has a through port, coupled port, and an isolated port. Port 1 is the input port, port 2 is the through port, port 3 is the isolated port and port 4 is the coupled port. When the couplers are equally split, power is evenly divided between the through port and the coupled port.



Consider the branchline coupler from “Splitters and Couplers”. The parameter values of this coupler are for a design frequency of 3 GHz. Calculate and plot the S-parameters of this coupler to understand its behavior.

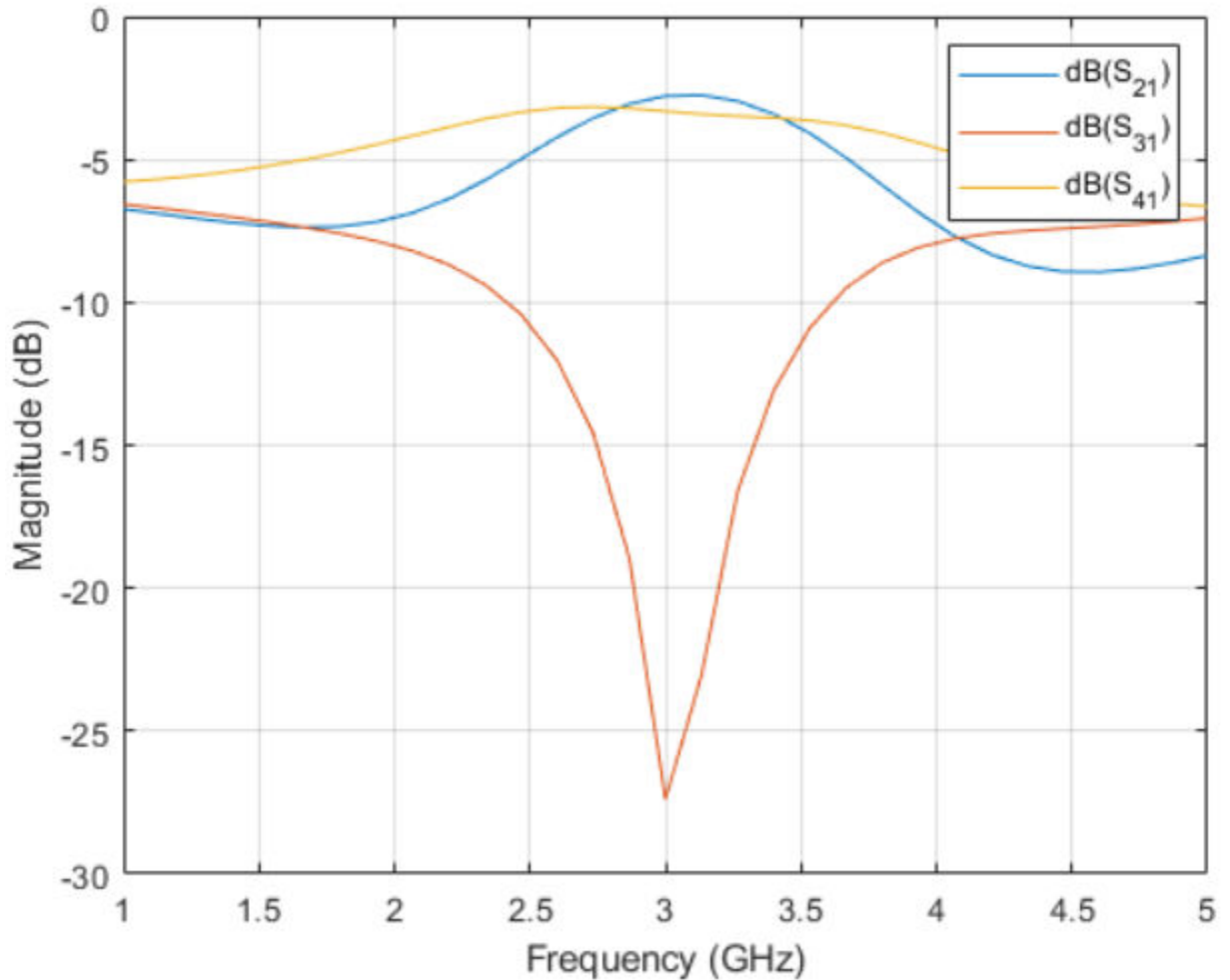
```
coupler = couplerBranchline;
spar = sparameters(coupler, linspace(1e9, 539, 50));
```

- `rfplot(spar,1,1)`  
`hold on`  
`rfplot(spar,2,2)`  
`hold on`  
`rfplot(spar,3,3)`  
`hold on`  
`rfplot(spar,4,4)`



All the reflection coefficients  $S_{11}$ ,  $S_{22}$ ,  $S_{33}$ , and  $S_{44}$  are close to -30 dB showing that the default branchline coupler has a good match at all ports.

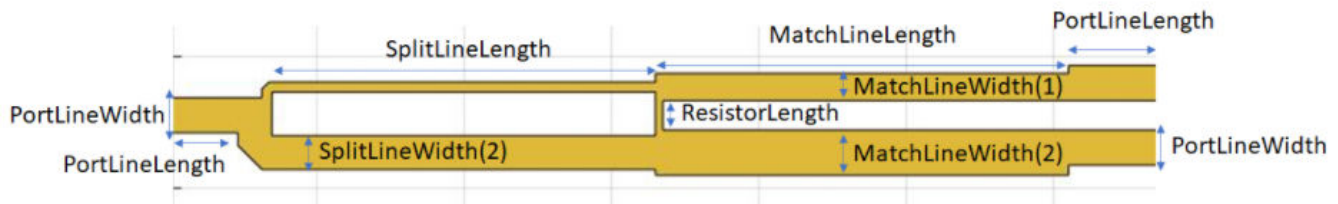
- `rfplot(spar,2,1)`  
`hold on`  
`rfplot(spar,3,1)`  
`hold on`  
`rfplot(spar,4,1)`



The transmission coefficients of  $S_{21}$  and  $S_{41}$  show that the power is equally divided between Port 2 and Port 4.  $S_{31}$  is -30 dB as Port 3 is isolated.

### S-Parameters of Unequal Wilkinson Splitter

An unequal Wilkinson splitter performs arbitrary power division between three ports based on the power ratio in the component design.



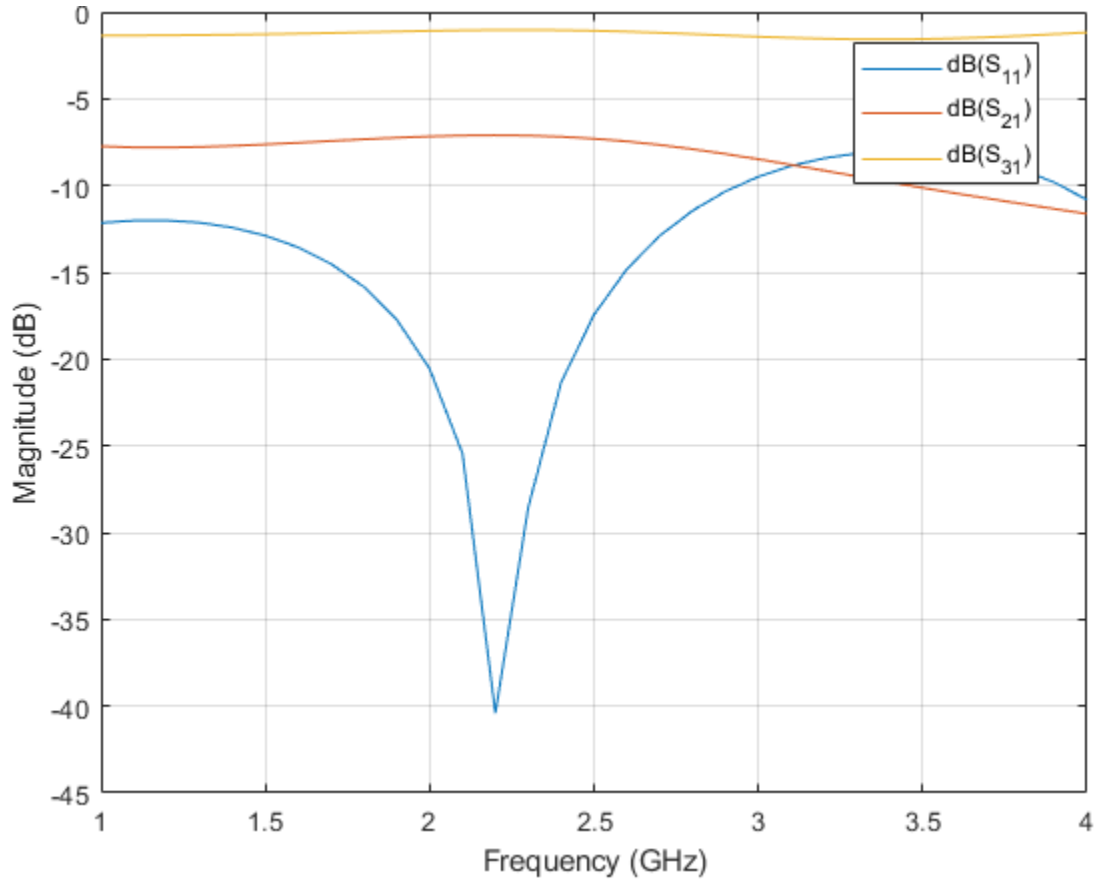
Consider an unequal Wilkinson splitter from “Splitters and Couplers”. Design it for a frequency of 2.5 GHz and with a power ratio of 4.

```
splitter = wilkinsonSplitterUnequal;
splitter = design(splitter, 2.5e9, 'PowerRatio', 2);
```

```

spar = sparameters(coupler, linspace(1e9, 4e9, 31));
rfplot(spar, 1, 1)
hold on
rfplot(spar, 2, 1)
hold on
rfplot(spar, 3, 1)

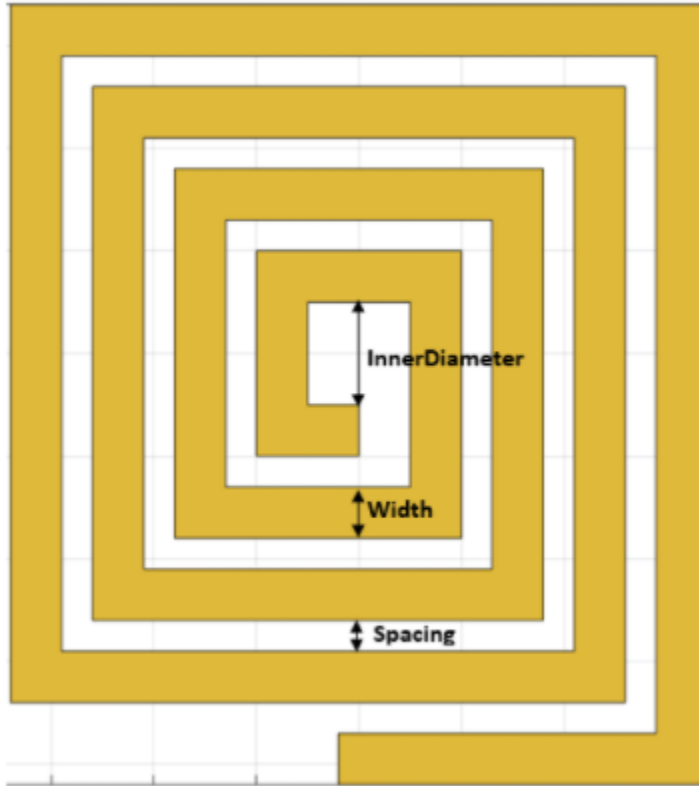
```



- The  $S_{11}$  reflection coefficient shows the value of -30 dB at 2.5 GHz, showing very little reflection at the design frequency.
- The  $S_{31}$  value is close to -0.97 dB and  $S_{21}$  value is -6.99 dB indicating unequal power division at the output ports based on the power ratio of 4.

### S-Parameters of Spiral Inductor

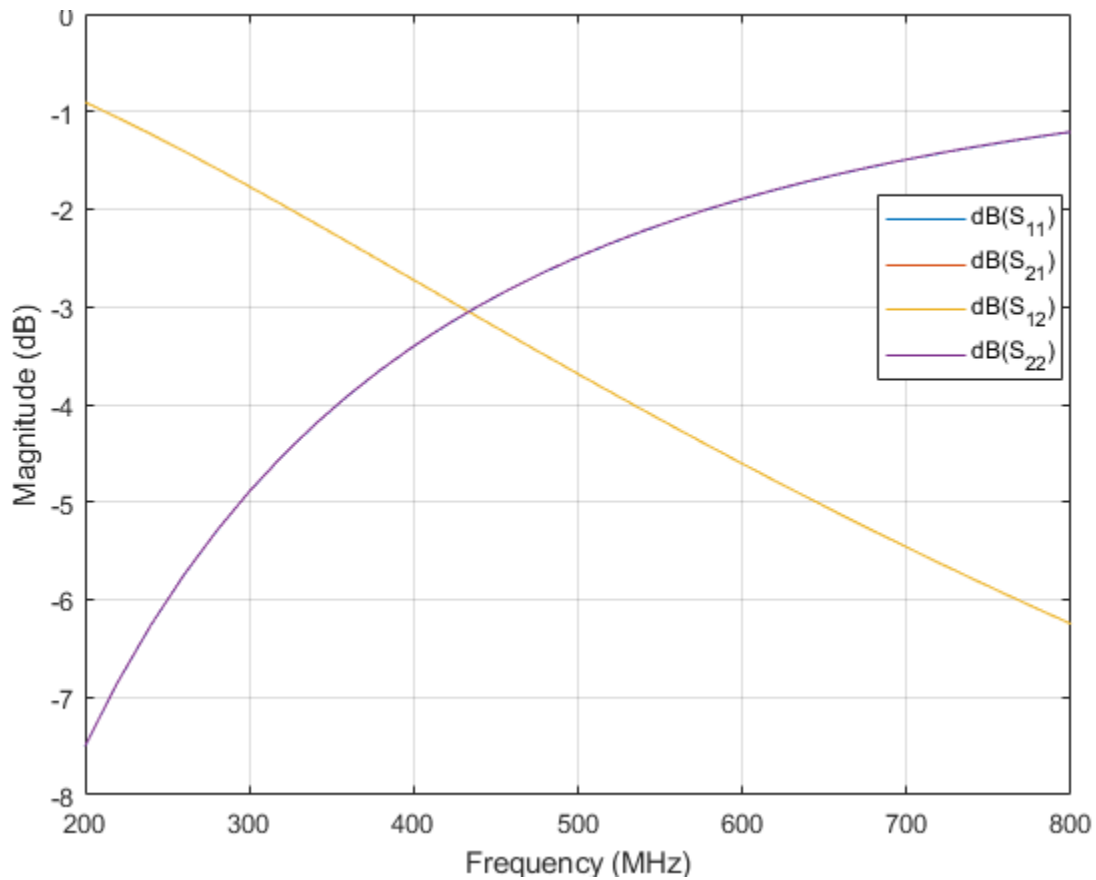
A spiral inductor is used as a microwave-resonant element in PCB circuits and as a choke in power supplies.



Consider a square spiral inductor from “Inductors and Capacitors”. Calculate and plot the S-parameters to show the power conservation at the default frequency of 600 MHz.

```
inductor = spiralInductor;  
spar = sparameters(inductor, linspace(200e6, 800e6, 31));  
rfplot(spar);
```





- The  $S_{11}$  and  $S_{22}$  values increase to 0 dB after 600 MHz..
- The  $S_{12}$  and  $S_{21}$  values decrease indicating that the energy is stored in the inductor and not radiated.
- The behavior of the  $S_{11}$  and  $S_{21}$  values satisfies the law of conservation of energy.

## See Also

sparameters

## More About

- “Behavioral Models” on page 3-12

## Behavioral Models

Behavioral modeling or black-box modeling does not require you to provide the specifications of all the physical systems in your model. The type of modeling depends on the input and output measurements of the component or systems.

In RF PCB Toolbox you can:

- Perform the behavioral analysis on a PCB component by using the `sparameters` function with the `Behavioral` property set to `true`.
- Convert a PCB component into a behavioral PCB element using the `pcbElement` object.

The components and shapes that support behavioral modeling are:

Bends	<ul style="list-style-type: none"> <li>• <code>bendRightAngle</code></li> <li>• <code>bendCurved</code></li> <li>• <code>bendMitered</code></li> </ul> <p><b>Note</b> The <code>sparameters</code> function does not support the behavioral model for objects with unequal widths such as <code>bendRightAngle</code>, <code>bendCurved</code>, and <code>bendMitered</code> objects.</p>
Traces	<ul style="list-style-type: none"> <li>• <code>traceTee</code></li> <li>• <code>traceCross</code></li> </ul> <p><b>Note</b> The <code>sparameters</code> function does not support the behavioral model for Asymmetric tee- and cross-junction traces.</p>
Transmission line objects	<ul style="list-style-type: none"> <li>• <code>microstripLine</code></li> <li>• <code>coplanarWaveguide</code></li> </ul>
Inductor	<code>spiralInductor</code>
Capacitor	<code>interdigitalCapacitor</code>

### Perform Behavioral Analysis of PCB Component

The main advantage of behavioral modeling as compared to full-wave electro-magnetic (EM) modeling is that you can analyze the PCB component faster using behavioral modeling.

Consider an interdigital capacitor with default properties. Calculate the S-parameters of this component.

```
capacitor = interdigitalCapacitor;
tic
sparameters(capacitor,4e9)
toc

ans =
```

```

sparameters: S-parameters object

    NumPorts: 2
    Frequencies: 4.0000e+09
    Parameters: [2x2 double]
    Impedance: 50

rfparam(obj,i,j) returns S-parameter Sij

```

Elapsed time is 176.844515 seconds.

The S-parameters function takes 176.9 seconds to run.

Now calculate the S-parameters of this capacitor with the Behavioral property in sparameters function set to true.

```

capacitor = interdigitalCapacitor;
tic
sparameters(capacitor,4e9,Behavioral=true)
toc

ans =

```

```

sparameters: S-parameters object

    NumPorts: 2
    Frequencies: 4.0000e+09
    Parameters: [2x2 double]
    Impedance: 50

rfparam(obj,i,j) returns S-parameter Sij

```

Elapsed time is 0.295000 seconds.

The S-parameters function takes 0.30 seconds.

## Convert PCB Component to Behavioral Circuit Element

You can convert a PCB component into a behavioral PCB element by using the `pcbElement` object, and then add this PCB element to an RF Toolbox™ circuit object. You can convert only PCB components that support behavioral analysis to behavioral PCB elements. For a complete list of objects and shapes that support behavioral analysis, see the introduction.

Create a RF Toolbox circuit objects of two interdigital capacitors. Use the behavioral model in the first capacitor and the full- wave model in the second capacitor.

```

ckt = circuit;
c1 = interdigitalCapacitor;
c2 = interdigitalCapacitor('NumFingers',3);
p = pcbElement(c2,'Behavioral',false);
add(ckt,[1 2 0 0],c1) % default pcbElement created automatically
add(ckt,[2 3 0 0],p)
setports(ckt,[1 0],[3 0])
tic
S = sparameters(ckt,8e9)
toc

```

```
S =  
  
  sparameters: S-parameters object  
  
    NumPorts: 2  
  Frequencies: 8.0000e+09  
  Parameters: [2x2 double]  
  Impedance: 50  
  
  rfparam(obj,i,j) returns S-parameter Sij
```

Elapsed time is 1.997850 seconds.

The S-parameters function takes 1.9 seconds.

Now calculate the S-parameters of the circuit with both capacitors as full-wave model circuit elements.

```
ckt = circuit;  
c1 = interdigitalCapacitor;  
c2 = interdigitalCapacitor('NumFingers',3);  
p1 = pcbElement(c1,'Behavioral',false);  
p2 = pcbElement(c2,'Behavioral',false);  
add(ckt,[1 2 0 0],p1) % default pcbElement created automatically  
add(ckt,[2 3 0 0],p2)  
setports(ckt,[1 0],[3 0])  
tic  
S = sparameters(ckt,8e9)  
toc
```

```
S =  
  
  sparameters: S-parameters object  
  
    NumPorts: 2  
  Frequencies: 8.0000e+09  
  Parameters: [2x2 double]  
  Impedance: 50  
  
  rfparam(obj,i,j) returns S-parameter Sij
```

Elapsed time is 3.482307 seconds.

The S-parameters function takes 3.5 seconds.

Comparing the two circuits shows a small difference in the time taken to calculate the S-parameters. Now consider an entire PCB board with many PCB components. You can perform behavioral modeling on almost all noncritical components and full-wave modeling on the critical components of a PCB board.

## See Also

sparameters

## More About

- “Scattering Parameters or S-Parameters” on page 3-4