

Mixed-Mode S-Parameters Analysis

Introduction

Mixed-mode S-parameters describe the responses of a circuit with balanced ports excited and terminated by two types of modes: common and differential modes. They are calculated using a full S-parameter matrix of a four-port network that is composed of four single ended lines. This example analyzes two adjacent microstrip lines and computes the mixed-mode S-parameters.



Figure 1: Microstrip line circuit board modeled with lumped ports for mixed-mode Sparameters calculation. The surrounding air domain is not included for visualization purposes.

Model Definition

The model consists of a pair of microstrip line adjacent to each other on a 20 mil substrate with a dielectric constant of $\varepsilon_r = 3.38$. One line has a discontinuity that is connected with a bonding wire. The bonding wire geometry is built with a half of torus that has a wire radius of 0.15 mm. All metallic parts, including the microstrip lines, the bottom ground plane, and the bonding wire surface, are set to perfect electric conductor (PEC), due to the negligible loss from the finite conductivity. The circuit is surrounded by an air domain.

The exterior surfaces of the air domain are finished by a scattering boundary condition – an absorbing boundary to describe an open radiating space.

On the physics interface settings, activate port sweep. With port sweep activated, a parametric sweep over the port name is added in the study. Thereby a full four-by-four S-parameter matrix is obtained. The S-parameter matrix is required to process the mixed-mode S-parameters. The balanced ports out of a four-port network are configured by a global feature called mixed-mode S-parameters where the balanced port 1 is composed of port 1 and 3, and the balanced port 2 is defined with port 2 and 4.



Figure 2: Balanced port configuration of a four port network in the mixed-mode S-parameter feature.

Based on the balanced port settings, the mixed-mode S-parameters are defined as

$$\mathbf{S}_{\text{mixed-mode}} = \frac{1}{2} \begin{bmatrix} \mathbf{S}_{\text{dd11}} \ \mathbf{S}_{\text{dd12}} \ \mathbf{S}_{\text{dc11}} \ \mathbf{S}_{\text{dc12}} \\ \mathbf{S}_{\text{dd21}} \ \mathbf{S}_{\text{dd22}} \ \mathbf{S}_{\text{dc21}} \ \mathbf{S}_{\text{dc22}} \\ \mathbf{S}_{\text{cd11}} \ \mathbf{S}_{\text{cd12}} \ \mathbf{S}_{\text{cc11}} \ \mathbf{S}_{\text{cc12}} \\ \mathbf{S}_{\text{cd21}} \ \mathbf{S}_{\text{cd21}} \ \mathbf{S}_{\text{cc11}} \ \mathbf{S}_{\text{cc22}} \end{bmatrix}$$

$$\begin{split} \mathbf{S}_{dd11} &= \frac{1}{2} (\mathbf{S}_{AA} - \mathbf{S}_{AB} - \mathbf{S}_{BA} + \mathbf{S}_{BB}), \ \mathbf{S}_{dd12} &= \frac{1}{2} (\mathbf{S}_{AC} - \mathbf{S}_{AD} - \mathbf{S}_{BC} + \mathbf{S}_{BD}) \\ \mathbf{S}_{dd21} &= \frac{1}{2} (\mathbf{S}_{CA} - \mathbf{S}_{CB} - \mathbf{S}_{DA} + \mathbf{S}_{DB}), \ \mathbf{S}_{dd22} &= \frac{1}{2} (\mathbf{S}_{CC} - \mathbf{S}_{CD} - \mathbf{S}_{DC} + \mathbf{S}_{DD}) \\ \mathbf{S}_{dc11} &= \frac{1}{2} (\mathbf{S}_{AA} + \mathbf{S}_{AB} - \mathbf{S}_{BA} - \mathbf{S}_{BB}), \ \mathbf{S}_{dc12} &= \frac{1}{2} (\mathbf{S}_{AC} + \mathbf{S}_{AD} - \mathbf{S}_{BC} - \mathbf{S}_{BD}) \\ \mathbf{S}_{dc21} &= \frac{1}{2} (\mathbf{S}_{CA} + \mathbf{S}_{CB} - \mathbf{S}_{DA} - \mathbf{S}_{DB}), \ \mathbf{S}_{dc22} &= \frac{1}{2} (\mathbf{S}_{CC} + \mathbf{S}_{CD} - \mathbf{S}_{DC} - \mathbf{S}_{DD}) \\ \mathbf{S}_{cd11} &= \frac{1}{2} (\mathbf{S}_{AA} - \mathbf{S}_{AB} + \mathbf{S}_{BA} - \mathbf{S}_{BB}), \ \mathbf{S}_{cd12} &= \frac{1}{2} (\mathbf{S}_{AC} - \mathbf{S}_{AD} + \mathbf{S}_{BC} - \mathbf{S}_{DD}) \\ \mathbf{S}_{cd21} &= \frac{1}{2} (\mathbf{S}_{CA} - \mathbf{S}_{CB} + \mathbf{S}_{DA} - \mathbf{S}_{DB}), \ \mathbf{S}_{cd22} &= \frac{1}{2} (\mathbf{S}_{CC} - \mathbf{S}_{CD} + \mathbf{S}_{DC} - \mathbf{S}_{DD}) \\ \mathbf{S}_{cd21} &= \frac{1}{2} (\mathbf{S}_{CA} - \mathbf{S}_{CB} + \mathbf{S}_{DA} - \mathbf{S}_{DB}), \ \mathbf{S}_{cd22} &= \frac{1}{2} (\mathbf{S}_{CC} - \mathbf{S}_{CD} + \mathbf{S}_{DC} - \mathbf{S}_{DD}) \end{split}$$

$$\begin{split} \mathbf{S}_{cc11} &= \frac{1}{2} (\mathbf{S}_{AA} + \mathbf{S}_{AB} + \mathbf{S}_{BA} + \mathbf{S}_{BB}), \ \mathbf{S}_{cc12} &= \frac{1}{2} (\mathbf{S}_{AC} + \mathbf{S}_{AD} + \mathbf{S}_{BC} + \mathbf{S}_{BD}) \\ \mathbf{S}_{cc21} &= \frac{1}{2} (\mathbf{S}_{CA} + \mathbf{S}_{CB} + \mathbf{S}_{DA} + \mathbf{S}_{DB}), \ \mathbf{S}_{cc22} &= \frac{1}{2} (\mathbf{S}_{CC} + \mathbf{S}_{CD} + \mathbf{S}_{DC} + \mathbf{S}_{DD}) \end{split}$$

where subscript c and d stand for common mode and differential mode, respectively. Each subscript of the mixed-mode S-parameters in the notation of S_{mnij} represents

- m: output observation mode
- n: input excitation mode
- i: output observation balanced port
- j: input excitation balanced port

All sixteen mixed-mode S-parameter components are listed in Table 1.

	OUTPUT MODE	INPUT MODE	OUTPUT PORT	INPUT PORT	
S _{cc11}	common	common	I	I	
S _{cc12}	common	common	I	2	
S _{cc21}	common	common	2	1	
S _{cc22}	common	common	2	2	
S _{cd I I}	common	differential	I	1	
S _{cd12}	common	differential	I	2	
S _{cd21}	common	differential	2	1	
S _{cd22}	common	differential	2	2	
S _{dc11}	differential	common	I	1	
S _{dc12}	differential	common	I	2	
S _{dc21}	differential	common	2	1	
S _{dc22}	differential	common	2	2	
S _{dd I I}	differential	differential	1	1	
S _{dd12}	differential	differential	1	2	
S _{dd21}	differential	differential	2	1	
S _{dd22}	differential	differential	2	2	

TABLE I: MIXED-MODE S-PARAMETER SUBSCRIPT DESCRIPTION.

Results and Discussion

Figure 3 shows the plot of the electric field norm when port 4 is excited. In this surface plot, there is no visible coupling effect to the adjacent microstrip line between port 1 and 2.



Figure 3: Electric field norm plot when port 4 is excited.

In Figure 4, the mixed-mode S-parameters, S_{cc11} , S_{cd12} , S_{dc21} , and S_{dd22} , are plotted. The level of mode conversion between common and differential modes increases as frequency increases.



Figure 4: The mixed-mode S-parameters. The cross-mode conversion between common and differential modes can be estimated from the mixed-mode S-parameters.

Application Library path: RF_Module/EMI_EMC_Applications/

microstrip_line_mixed_mode

Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click 🙆 Model Wizard.

MODEL WIZARD

- I In the Model Wizard window, click 间 3D.
- 2 In the Select Physics tree, select Radio Frequency>Electromagnetic Waves, Frequency Domain (emw).

- 3 Click Add.
- 4 Click \bigcirc Study.
- 5 In the Select Study tree, select General Studies>Frequency Domain.
- 6 Click 🗹 Done.

GLOBAL DEFINITIONS

Parameters 1

- I In the Model Builder window, under Global Definitions click Parameters I.
- 2 In the Settings window for Parameters, locate the Parameters section.
- **3** In the table, enter the following settings:

Name	Expression	Value	Description
sub_l	15[mm]	0.015 m	Substrate length
sub_w	15[mm]	0.015 m	Substrate width
sub_t	20[mil]	5.08E-4 m	Substrate thickness
line_w	1.13[mm]	0.00113 m	Line width

It is convenient to define parameters for frequently used values. Here, mil refers to the unit milliinch.

GEOMETRY I

- I In the Model Builder window, under Component I (compl) click Geometry I.
- 2 In the Settings window for Geometry, locate the Units section.
- 3 From the Length unit list, choose mm.

Add a box for the substrate geometry.

Block I (blkI)

- I In the **Geometry** toolbar, click 🗍 **Block**.
- 2 In the Settings window for Block, locate the Size and Shape section.
- 3 In the Width text field, type sub_1.
- 4 In the **Depth** text field, type sub_w.
- 5 In the **Height** text field, type sub_t.
- 6 Locate the **Position** section. In the **z** text field, type sub_t/2.
- 7 From the Base list, choose Center.

Draw two microstrip line patterns on top of the substrate.

Work Plane I (wp1)

- I In the Geometry toolbar, click 📥 Work Plane.
- 2 In the Settings window for Work Plane, locate the Plane Definition section.
- 3 In the z-coordinate text field, type sub_t.

Work Plane I (wpI)>Plane Geometry

In the Model Builder window, click Plane Geometry.

Work Plane I (wp1)>Rectangle I (r1)

- I In the Work Plane toolbar, click Rectangle.
- 2 In the Settings window for Rectangle, locate the Size and Shape section.
- 3 In the Width text field, type 5.
- 4 In the **Height** text field, type line_w.
- 5 Locate the Position section. From the Base list, choose Center.

Work Plane I (wp1)>Rotate I (rot1)

- I In the Work Plane toolbar, click 💭 Transforms and choose Rotate.
- 2 Select the object rI only.



- 3 In the Settings window for Rotate, locate the Rotation section.
- 4 In the Angle text field, type 45.
- 5 Click 📄 Build Selected.

Work Plane 1 (wp1)>Rectangle 2 (r2)

- In the Model Builder window, under Component I (compl)>Geometry I>
 Work Plane I (wpl)>Plane Geometry right-click Rectangle I (rl) and choose Duplicate.
- 2 In the Settings window for Rectangle, locate the Size and Shape section.
- 3 In the Width text field, type sub_1/2-5/2/sqrt(2)+line_w/2/sqrt(2).
- 4 Locate the Position section. In the xw text field, type -sub_1/2+(sub_1/2-5/2/sqrt(2)+line_w/2/sqrt(2))/2.
- 5 In the yw text field, type -5/2/sqrt(2)+(line_w/2-line_w/2/sqrt(2)).

Work Plane I (wp1)>Rotate 2 (rot2)

I In the Work Plane toolbar, click 💭 Transforms and choose Rotate.

- 2 Select the object r2 only.
- 3 In the Settings window for Rotate, locate the Input section.
- **4** Select the **Keep input objects** check box.
- 5 Locate the Rotation section. In the Angle text field, type 180.
- 6 Click 틤 Build Selected.

Work Plane I (wp1)>Union I (uni1)

- I In the Work Plane toolbar, click 📕 Booleans and Partitions and choose Union.
- 2 Click in the Graphics window and then press Ctrl+A to select all objects.
- 3 In the Settings window for Union, locate the Union section.
- 4 Clear the Keep interior boundaries check box.

Work Plane I (wp1)>Move I (mov1)

I In the Work Plane toolbar, click [] Transforms and choose Move.

2 Select the object unil only.



- 3 In the Settings window for Move, locate the Displacement section.
- 4 In the **yw** text field, type 3.

Work Plane 1 (wp1)>Mirror 1 (mir1) I In the Work Plane toolbar, click 2 Transforms and choose Mirror.

2 Select the object mov1 only.



- 3 In the Settings window for Mirror, locate the Normal Vector to Line of Reflection section.
- 4 In the **xw** text field, type 0.
- **5** In the **yw** text field, type **1**.
- 6 Click 틤 Build Selected.
- 7 Locate the Input section. Select the Keep input objects check box.
- 8 Click 틤 Build Selected.

Work Plane I (wpI)>Rectangle 3 (r3)

- I In the Work Plane toolbar, click Rectangle.
- 2 In the Settings window for Rectangle, locate the Size and Shape section.
- 3 In the Width text field, type 2.
- 4 In the Height text field, type line_w.
- 5 Locate the Position section. From the Base list, choose Center.

Work Plane I (wp1)>Rotate 3 (rot3)

I In the Work Plane toolbar, click 💭 Transforms and choose Rotate.

2 Select the object **r3** only.



- 3 In the Settings window for Rotate, locate the Rotation section.
- 4 In the Angle text field, type -45.

Work Plane I (wp1)>Move 2 (mov2)

I In the Work Plane toolbar, click 👰 Transforms and choose Move.

2 Select the object rot3 only.



- 3 In the Settings window for Move, locate the Displacement section.
- 4 In the **yw** text field, type -3.

Work Plane I (wp1)>Difference I (dif1)

I In the Work Plane toolbar, click 💻 Booleans and Partitions and choose Difference.

2 Select the object mirl only.



- 3 In the Settings window for Difference, locate the Difference section.
- **4** Find the **Objects to subtract** subsection. Click to select the **Selection** toggle button.
- **5** Select the object **mov2** only.





By extruding the pattern, the boundaries for the four lumped ports can be created.

Extrude 1 (ext1)

- I In the Model Builder window, right-click Geometry I and choose Extrude.
- 2 In the Settings window for Extrude, locate the Distances section.
- **3** In the table, enter the following settings:

Distances (mm)

sub_t

4 Select the **Reverse direction** check box.

5 Click 틤 Build Selected.



Add a structure representing a bonding wire.

Torus I (tor I)

- I In the **Geometry** toolbar, click 😐 **Torus**.
- 2 In the Settings window for Torus, locate the Size and Shape section.
- 3 In the Major radius text field, type 1.3.
- 4 In the Minor radius text field, type 0.15.
- 5 In the **Revolution angle** text field, type 180.
- 6 Locate the Position section. In the z text field, type sub_t.
- 7 Locate the Axis section. From the Axis type list, choose y-axis.
- 8 Locate the Rotation Angle section. In the Rotation text field, type 90.
- 9 Click 🔚 Build Selected.

Rotate I (rotI)

I In the Geometry toolbar, click 📿 Transforms and choose Rotate.

2 Select the object torl only.



- 3 In the Settings window for Rotate, locate the Rotation section.
- 4 In the Angle text field, type -45.

Move I (movI)

I In the **Geometry** toolbar, click 💭 **Transforms** and choose **Move**.

2 Select the object **rot1** only.



- 3 In the Settings window for Move, locate the Displacement section.
- 4 In the y text field, type -3.
- 5 Click 🔚 Build Selected.



Add a box for the air domain.

Block 2 (blk2)

- I In the **Geometry** toolbar, click **[]** Block.
- 2 In the Settings window for Block, locate the Size and Shape section.
- **3** In the **Width** text field, type sub_1+4[mm].
- 4 In the **Depth** text field, type sub_w+2[mm].
- 5 In the Height text field, type sub_t*15.
- 6 Locate the **Position** section. In the **x** text field, type -sub_1/2-2[mm].
- 7 In the y text field, type sub_w/2-1[mm].
- 8 In the z text field, type -1[mm].
- 9 Click 🟢 Build All Objects.
- **10** Click the **Wireframe Rendering** button in the **Graphics** toolbar. See the interior using the wireframe rendering.



ADD MATERIAL

- I In the Home toolbar, click 🙀 Add Material to open the Add Material window.
- 2 Go to the Add Material window.
- 3 In the tree, select Built-in>Air.
- 4 Click Add to Component in the window toolbar.
- 5 In the Home toolbar, click 🙀 Add Material to close the Add Material window.

MATERIALS

Material 2 (mat2)

- I In the Model Builder window, under Component I (compl) right-click Materials and choose Blank Material.
- **2** Select Domains 2–5 and 7 only.



- 3 In the Settings window for Material, locate the Material Contents section.
- **4** In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	3.38	I	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

Assign Perfect Electric Conductor on all metal boundaries.

Perfect Electric Conductor 2

- I In the Model Builder window, under Component I (comp1) right-click Electromagnetic Waves, Frequency Domain (emw) and choose the boundary condition Perfect Electric Conductor.
- 2 Click the Select Box button in the Graphics toolbar.
- **3** Select Boundaries 8, 12, 13, 18, 19, 22, 31–38, 41, and 42 only. These are the boundaries of all metallic parts, including the microstrip lines, the bottom ground plane, and the bonding wire surface.



Add Lumped Ports on the boundaries between the microstrip lines and the ground plane.

Lumped Port I

I In the Physics toolbar, click 📄 Boundaries and choose Lumped Port.

2 Select Boundary 16 only.



Lumped Port 2

- I In the Physics toolbar, click 📄 Boundaries and choose Lumped Port.
- **2** Select Boundary 52 only.



Lumped Port 3

- I In the Physics toolbar, click 📄 Boundaries and choose Lumped Port.
- **2** Select Boundary 10 only.





2 Select Boundary 50 only.



Add Scattering Boundary Condition to absorb any radiation from the circuit board.

Scattering Boundary Condition 1

- I In the Physics toolbar, click 📄 Boundaries and choose Scattering Boundary Condition.
- **2** Select Boundaries 1–5 and 54 only.
- **3** Click the 🔁 Wireframe Rendering button in the Graphics toolbar.

4 Click the Transparency button in the Graphics toolbar.



The **Mixed-Mode S-parameters** global feature configures balanced ports and generates a four by four mixed mode S-parameter matrix.

Mixed-Mode S-Parameters I

- I In the Physics toolbar, click 🖗 Global and choose Mixed-Mode S-Parameters.
- 2 In the Settings window for Mixed-Mode S-Parameters, locate the Balanced Port section.
- **3** In the **Port name for port B in balanced pair I** text field, type **3**. **Balanced pair I** includes port 1 and port **3**.
- **4** In the **Port name for port C in balanced pair 2** text field, type **2**. **Balanced pair 2** includes port 2 and port 4.

let us set up the physics properties.

- 5 In the Model Builder window, click Electromagnetic Waves, Frequency Domain (emw).
- 6 In the Settings window for Electromagnetic Waves, Frequency Domain, locate the Port Sweep Settings section.
- 7 Select the Use manual port sweep check box.
- 8 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. It is necessary to run the parametric sweep with port names to get a full S-parameter matrix and build the mixed mode S-parameters.

MESH I

- I In the Model Builder window, under Component I (comp1) right-click Mesh I and choose Build All.
- **2** Click the Transparency button in the Graphics toolbar.

Hide some boundaries to get a better view of the interior parts.

DEFINITIONS

Hide for Physics 1

- I In the Model Builder window, expand the Component I (compl)>Definitions node.
- 2 Right-click View I and choose Hide for Physics.
- 3 In the Settings window for Hide for Physics, locate the Geometric Entity Selection section.
- 4 From the Geometric entity level list, choose Boundary.
- **5** Select Boundaries 1, 2, and 4 only.



MESH I



STUDY I

Step 1: Frequency Domain

- I In the Model Builder window, under Study I click Step I: Frequency Domain.
- 2 In the Settings window for Frequency Domain, locate the Study Settings section.
- 3 Click Range.
- 4 In the Range dialog box, type 1[GHz] in the Start text field.
- **5** In the **Step** text field, type **0.5**[GHz].
- 6 In the **Stop** text field, type 3[GHz].
- 7 Click Replace.
- 8 In the **Home** toolbar, click **= Compute**.

Disable the default field plot and add a volume plot.

RESULTS

Multislice

I In the Model Builder window, expand the Results>Electric Field (emw) node.

2 Right-click Multislice and choose Disable.

Volume 1

In the Model Builder window, right-click Electric Field (emw) and choose Volume.

Selection 1

- I In the Model Builder window, right-click Volume I and choose Selection.
- **2** Select Domains 2–7 only.

These are all domains except for the air domain.

Volume 1

- I In the Model Builder window, click Volume I.
- 2 In the Settings window for Volume, locate the Coloring and Style section.
- 3 Click Change Color Table.
- 4 In the Color Table dialog box, select Thermal>HeatCameraLight in the tree.
- 5 Click OK.
- 6 In the Settings window for Volume, locate the Coloring and Style section.
- 7 From the Color table transformation list, choose Reverse.

Electric Field (emw)

- I In the Model Builder window, click Electric Field (emw).
- 2 In the Settings window for 3D Plot Group, locate the Plot Settings section.
- **3** Clear the **Plot dataset edges** check box.
- 4 In the Electric Field (emw) toolbar, click 💿 Plot.

This reproduces Figure 3, the volume plot of the circuit board when port 4 is excited.

S-parameter (emw)

- I In the Model Builder window, click S-parameter (emw).
- 2 In the Settings window for ID Plot Group, locate the Data section.
- 3 From the Dataset list, choose Study I/Solution I (soll).
- 4 Locate the Legend section. From the Position list, choose Lower right.

Global I

- I In the Model Builder window, expand the S-parameter (emw) node, then click Global I.
- 2 In the Settings window for Global, locate the y-Axis Data section.
- 3 Click 📐 Clear Table.

- 4 Click Add Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (comp1)>Electromagnetic Waves, Frequency Domain>Mixed-Mode S-Parameters 1>S-parameter, dB, common mode to common mode>emw.Scc11dB -Scc11.
- 5 Click Add Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (comp1)>Electromagnetic Waves, Frequency Domain>Mixed-Mode S-Parameters 1>S-parameter, dB, common mode to differential mode> emw.Scd12dB Scd12.
- 6 Click Add Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (comp1)>Electromagnetic Waves, Frequency Domain>Mixed-Mode S-Parameters 1>S-parameter, dB, differential mode to common mode> emw.Sdc21dB Sdc21.
- 7 Click Add Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (comp1)>Electromagnetic Waves, Frequency Domain>Mixed-Mode S-Parameters 1>S-parameter, dB, differential mode to differential mode> emw.Sdd22dB - Sdd22.
- 8 Click to expand the Coloring and Style section. Find the Line markers subsection. From the Marker list, choose Cycle.
- 9 In the S-parameter (emw) toolbar, click 💽 Plot.

Compare to Figure 4, the global 1D plot of the mixed mode S-parameters.