Created in COMSOL Multiphysics 6.1

Three-Port Ferrite Circulator

Introduction

A microwave circulator is a multiport device that has the property that a wave incident in port 1 is coupled into port 2 only, a wave incident in port 2 is coupled into port 3 only, and so on. A circulator is used to isolate microwave components to couple a transmitter and a receiver to a common antenna, for example. They typically rely on the use of anisotropic materials, most commonly ferrites. In this example, a three-port circulator is constructed from three rectangular waveguide sections joining at 120° where a ferrite post is inserted at the center of the joint. Figure 1 shows the geometry of the circulator.

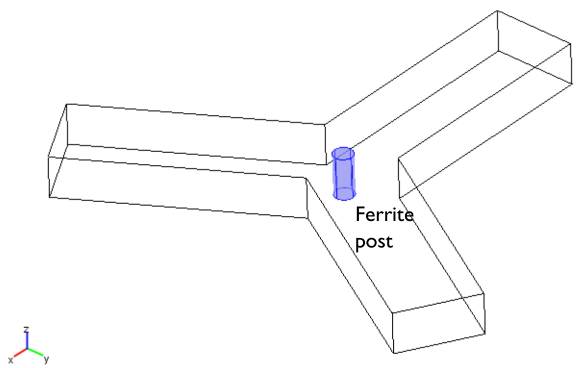


Figure 1: Geometry of the three-port microwave circulator.

To match the junction, identical dielectric tuning elements are inserted into each branch (not shown above). The ferrite post is magnetized by a static H_0 bias field along the axis. The bias field is usually supplied by external permanent magnets. Here, the focus is on the modeling of the ferrite and how to minimize reflections at the inport by matching the junction by the proper choice of tuning elements. For a general introduction to the modeling of rectangular waveguide structures, see the model H-Bend Waveguide 3D. Matching the circulator junction involves calculating how well a TE_{10} wave propagates between ports in the circulator for different materials in the tuning element. This is done by calculating the scattering parameters, or S-parameters, of the structure as a function of the permittivity of the tuning elements for the fundamental TE_{10} mode. The S-parameters are a measure of the transmittance and reflectance of the circulator. For a theoretical background on S-parameters, see the section *S-Parameters and Ports* in the *RF Module User's Guide*.

This example only includes the TE_{10} mode of the waveguide. Thus the model can be made in 2D as the fields of the TE_{10} mode have no variation in the transverse direction. Figure 2 shows the 2D geometry including the dielectric tuning elements.

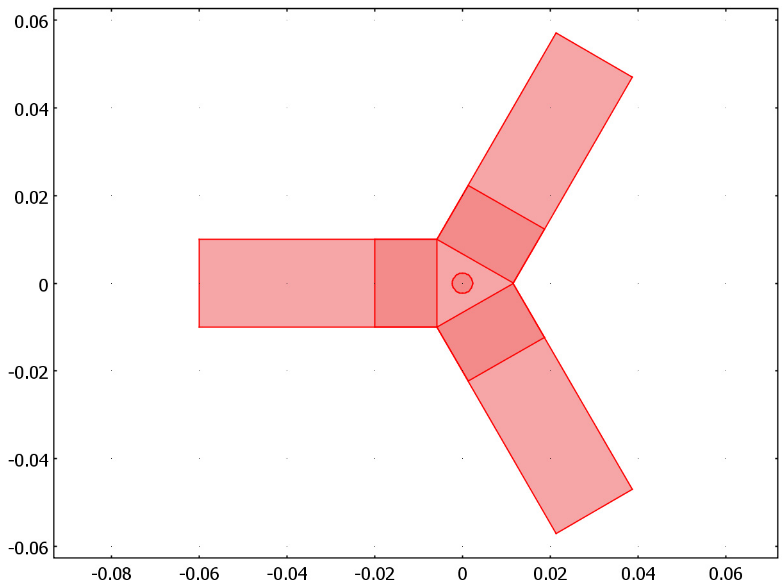


Figure 2: 2D geometry with dielectric tuning elements.

Model Definition

The dependent variable in this physics interface is the z-component of the electric field $\mathbf{E}$. It obeys the following relation:

$$\nabla\times(\mu_r^{-1}\nabla\times E_z)-\left(\varepsilon_r-\frac{j\sigma}{\omega\varepsilon_0}\right)k_0^2E_z = 0$$

where μ_r denotes the relative permeability, ω the angular frequency, σ the conductivity, ε_0 the permittivity of vacuum, ε_r the relative permittivity, and k_0 is the free space wave number. Losses are neglected so the conductivity is zero everywhere. The magnetic permeability is of key importance in this example as it is the anisotropy of this parameter that is responsible for the nonreciprocal behavior of the circulator. For the theory of the magnetic properties of ferrites, see Ref. 1 and Ref. 2. The model assumes that the static magnetic bias field, H_0, is much stronger than the alternating magnetic field of the microwaves, so the quoted results are a linearization for a small-signal analysis around this operating point. Further assume that the applied magnetic bias field is strong enough for the ferrite to be in magnetic saturation. Under these assumptions and neglecting losses, the anisotropic permeability of a ferrite magnetized in the positive z direction is given by:

$$[\mu] = \begin{bmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix}$$

where

$$\kappa = \mu_0\left(\frac{\omega\omega_m}{\omega_0^2 - \omega^2}\right)$$

$$\mu = \mu_0\left(1 + \frac{\omega_0\omega_m}{\omega_0^2 - \omega^2}\right)$$

and

$$\omega_0 = \mu_0\gamma H_0$$

$$\omega_m = \mu_0\gamma M_s$$

Here μ_0 denotes the permeability of free space; ω is the angular frequency of the microwave field; ω_0 is the precession frequency or Larmor frequency of a spinning electron in the applied magnetic bias field, H_0; ω_m is the electron Larmor frequency at the saturation magnetization of the ferrite, M_s; and γ is the gyromagnetic ratio of the electron. For a lossless ferrite, the permeability clearly becomes unbounded at $\omega = \omega_0$. In a real ferrite, this resonance becomes finite and is broadened due to losses. For complete expressions including losses, see Ref. 1 and Ref. 2. In this analysis the operating frequency is chosen sufficiently off from the Larmor frequency to avoid the singularity. The material data, $M_s = 2.39 \cdot 10^5$ A/m and $\varepsilon_r = 12.9$, are taken for magnesium ferrite from Ref. 2. The applied bias field is set to $H_0 = 2.72 \cdot 10^5$ A/m, which is well above saturation. The electron gyromagnetic ratio is set to $1.759 \cdot 10^{11}$ C/kg. Finally, the model uses an operating frequency of 10 GHz. This is well above the cutoff for the TE_{10} mode, which for a waveguide cross section of 2 cm by 1 cm is at about 7.5 GHz. At the ports, matched port boundary conditions make the boundaries transparent to the wave.

Results and Discussion

The S_{11} parameter as a function of the relative permittivity of the matching elements, `eps_r`, is shown in Figure 3. The S_{11} parameter corresponds to the reflection coefficient at port 1. Thus matching the junction is equivalent to minimizing the magnitude of S_{11}.

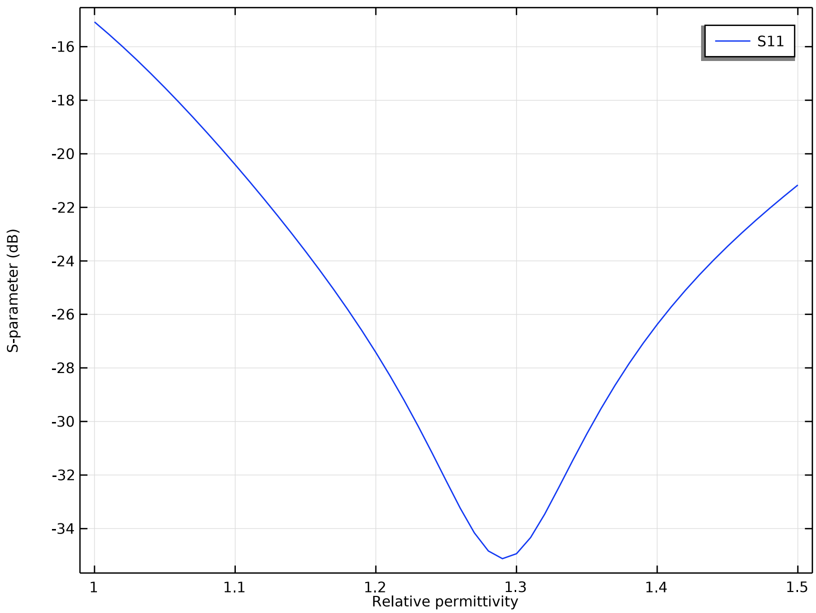
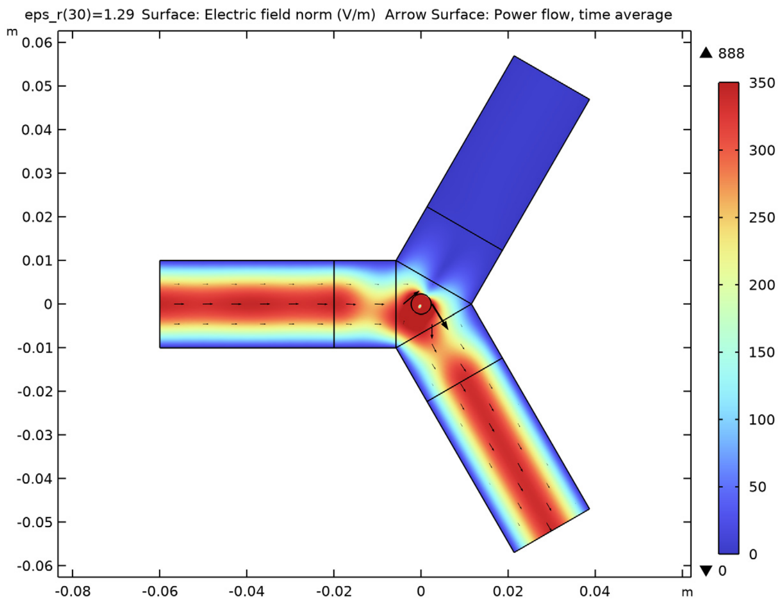


Figure 3: S_{11} parameter as a function of the relative permittivity.

By choosing `eps_r` to about 1.29, you obtain a reflection coefficient of about –35 dB, which is a good value for a circulator design. Judging from the absence of standing wave patterns in the magnitude plot of the electric field and by looking at the direction of the microwave energy flow in the result plot below, it is clear that the circulator behaves as desired.



References

1. R.E. Collin, *Foundations for Microwave Engineering*, 2nd ed., IEEE Press/Wiley-Interscience, 2000.

2. D.M. Pozar, *Microwave Engineering*, 3rd ed., John Wiley & Sons, 2004.

Application Library path: `RF_Module/Ferrimagnetic_Devices/circulator`

Modeling 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>Electromagnetic Waves, Frequency Domain (emw)**.
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 In the table, enter the following settings:

Name	Expression	Value	Description
eps_r	1	1	Relative permittivity

GEOMETRY 1

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.
2 In the **Settings** window for **Import**, locate the **Import** section.
3 Click **Browse**.
4 Browse to the model's Application Libraries folder and double-click the file `circulator.mphbin`.
5 Click **Import**.
6 Click the **Zoom Extents** button in the **Graphics** toolbar.

ADD MATERIAL

1 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

Air (mat1)

Select Domains 1, 3, 6, and 7 only.

Define the dielectric matching elements with a permittivity eps_r. You will later set up the solver to sweep this parameter.

Dielectric

1 In the **Model Builder** window, right-click **Materials** and choose **Blank Material**.
2 In the **Settings** window for **Material**, type `Dielectric` in the **Label** text field.
3 Select Domains 2, 4, and 5 only.
4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	`eps_r`	1	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

Ferrite

1 Right-click **Materials** and choose **Blank Material**.
2 In the **Settings** window for **Material**, type `Ferrite` in the **Label** text field.
3 Select Domain 8 only.

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

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	`12.9`	1	Basic
Relative permeability	{mur11, mur21, mur31, mur12, mur22, mur32, mur13, mur23, mur33}	`{mur,-i*kr,0,i*kr,mur,0,0,0,1}`	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

5 In the **Model Builder** window, expand the **Component 1 (comp1)>Materials>Ferrite (mat3)** node, then click **Basic (def)**.

6 In the **Settings** window for **Basic**, locate the **Model Inputs** section.

7 Click **Select Quantity**.

8 In the **Physical Quantity** dialog box, type `frequency` in the text field.

9 Click **Filter**.

10 In the tree, select **General>Frequency (Hz)**.

11 Click **OK**.

To define mur and kr in terms of the frequency, you need to enter a number of local parameters.

12 In the **Settings** window for **Basic**, locate the **Local Properties** section.

13 In the **Local properties** table, enter the following settings:

Name	Expression	Unit	Description
`gamma`	`1.759e11[C/kg]`	C/kg	
`omega`	`2*pi*freq`	Hz	

Name	Expression	Unit	Description
H0	omega/(gamma*mu0_const+1e4[m/C])	A/m	
w0	mu0_const*gamma*H0	1/s	
Ms	0.3[Wb/m^2]/mu0_const	A/m	
wm	mu0_const*gamma*Ms	1/s	
mur	1+w0*wm/(w0^2-omega^2)		
kr	omega*wm/(w0^2-omega^2)		

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

With the Electromagnetic Waves interface selected and the materials defined, the physics you need to specify is only the ports.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.

2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.

3 From the **Electric field components solved for** list, choose **Out-of-plane vector**.

Only the z-component of electric field (transverse electric mode) is effective in the simulation domain. By choosing the **Out-of-plane vector**, the computation can be more efficient.

Port 1

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

2 Select Boundary 1 only.

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

4 From the **Type of port** list, choose **Rectangular**.

For the first port, wave excitation is **on** by default.

Port 2

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

2 Select Boundary 20 only.

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

4 From the **Type of port** list, choose **Rectangular**.

Port 3

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

2 Select Boundary 21 only.

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

4 From the **Type of port** list, choose **Rectangular**.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 In the table, clear the **Use** check box for **Electromagnetic Waves, Frequency Domain (emw)**.

4 From the **Element size** list, choose **Finer**.

5 Click **Build All**.

STUDY 1

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
eps_r (Relative permittivity)	`range(1,0.01,1.5)`	

Step 1: Frequency Domain

1 In the **Model Builder** window, 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 `10[GHz]`.

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

RESULTS

Electric Field (emw)

The default plot shows the norm of the electric field for eps_r = 1.5. The plot is dominated by the strong field in the ferrite post. Adjust the range to get a better overview of the fields throughout the circulator, and add arrows representing the power flow.

Surface

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

2 In the **Settings** window for **Surface**, click to expand the **Range** section.

3 Select the **Manual color range** check box.

4 In the **Maximum** text field, type 350.

5 In the **Electric Field (emw)** toolbar, click **Plot**.

Arrow Surface 1

1 In the **Model Builder** window, right-click **Electric Field (emw)** and choose **Arrow Surface**.

2 In the **Settings** window for **Arrow Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Energy and power>emw.Poavx,emw.Poavy - Power flow, time average**.

3 Locate the **Arrow Positioning** section. Find the **Y grid points** subsection. In the **Points** text field, type 25.

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

5 In the **Electric Field (emw)** toolbar, click **Plot**.

The presence of standing waves in the input arm is clearly visible for this value (1.5) of the relative permittivity in the matching elements. To study how the reflections depend on the value of this parameter, plot the reflection coefficient S_{11} as a function of eps_r.

Global 1

1 In the **Model Builder** window, expand the **Results>S-parameter (emw)** node, then click **Global 1**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain>Ports>S-parameter, dB>emw.S11dB - S11**.

3 In the **S-parameter (emw)** toolbar, click **Plot**.

The plot shows that eps_r = 1.29 gives the minimum reflection. You can study the field distribution for this solution by selecting it as follows:

Electric Field (emw)

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

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

3 From the **Parameter value (eps_r)** list, choose **1.29**.

4 In the **Electric Field (emw)** toolbar, click **Plot**.