Model created in COMSOL Multiphysics 6.4

Bow-Tie Antenna Optimization

Introduction

A bow tie antenna patterned on a dielectric substrate is optimized by adjusting the length of the arms and the flare angle to reduce the magnitude of S_{11}, reflection coefficient. The two geometric dimensions used as design variables directly control the antenna's size and shape, and also affect the dimensions of the dielectric substrate. The Efficient Global Optimization (EGO) method is employed to improve the objective function, $|S_{11}|$ and a reliability analysis is conducted to assess the robustness of the optimized design with respect to design parameter variations.

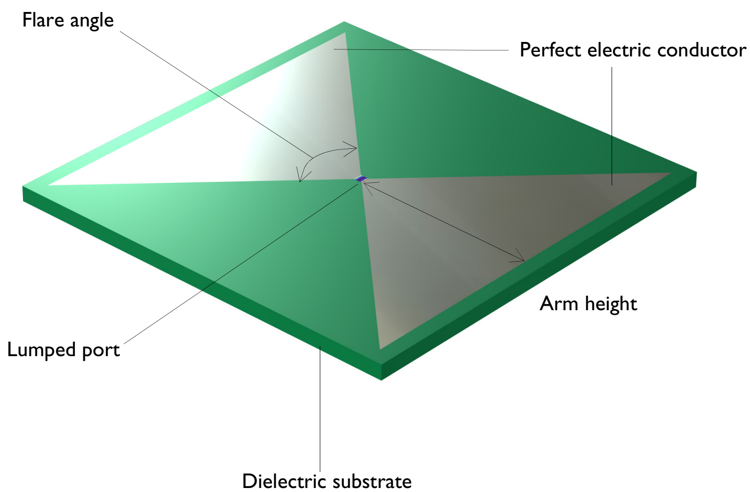


Figure 1: Outline of a bow tie antenna on a dielectric substrate.

Model Definition

The bow tie antenna model consists of a rectangular dielectric substrate with two triangular metal patterns on top, as shown in Figure 1. The flare angle and the height of the arms define the antenna's shape. To keep the substrate size minimal, it is defined to extend 2 mm beyond the antenna pattern. A lumped port excitation is applied to a small rectangular face between the antenna arms, simulating a 50 Ω transmission line feed.

The two design variables, flare angle and arm height, control a total of four dimensions in the model. The height and width of the rectangular dielectric substrate are slightly larger than the antenna profile. Consequently, the two design variables directly influence two other geometric dimensions in the model, which in turn affect the antenna characteristics.

EFFICIENT GLOBAL OPTIMIZATION

The reflection coefficient, $|S_{11}|$, is minimized using the Efficient Global Optimization (EGO) method. EGO is designed for optimizing complex, costly-to-evaluate functions by employing surrogate models, such as Gaussian Processes. It iteratively refines these models to predict the objective function, $|S_{11}|$ and uses the Monte Carlo method to maximize the acquisition function to decide the next point to evaluate, effectively analyzing problems where the function evaluation are expensive. By improving the surrogate model and sampling efficiently, EGO finds optimal solutions with a limited number of evaluations.

Due to the nonanalytic nature of the objective function, derivatives cannot be computed analytically with respect to the design variables. Additionally, the design parameters introduce significant geometric changes to the computational domains and can generate multiple minima during optimization. These factors necessitate the use of the EGO, a gradient-free optimization method, suitable as it does not require gradient information and helps avoid local minima. Using this approximate gradient information, the objective function is iteratively improved until the design variables converge within the desired tolerance.

RELIABILITY ANALYSIS

The Gaussian Process surrogate model used for the EGO is reused to perform a reliability analysis as part of uncertainty quantification with design parameter variations. The reliability analysis determines the probability that a specific condition related to the Quantity of Interest (QoI) will be satisfied. It evaluates the likelihood of meeting a predefined criterion based on the QoI. For example, it calculates the probability that the S-parameter is below –10 dB, helping to assess the reliability of meeting performance specifications. The S-parameter S_{11} in dB indicates the level of reflection or impedance mismatch at the antenna input port. The threshold of –10 dB is conventionally used, and when it is lower than –10 dB, the reflection due to the impedance mismatch is considered acceptable.

TABLE 1: INPUT PARAMETERS FOR RELIABILITY ANALYSIS

Parameter	Description	Mean	Standard deviation (σ)	Range
h0	Arm height	1.4295 mm	0.045*h0	h0 ± 2σ
theta	Flare angle	30°	0.045*theta	theta ± 2σ

Note: In addition to the RF Module, this example requires the Optimization Module.

Results and Discussion

The model is analyzed at a single frequency of 30 GHz. The optimizer adjusts the flare angle and arm height to reduce the reflection coefficient. For the initial, unoptimized design, $|S_{11}|$ is approximately 0.645, while for the optimized design, $|S_{11}|$ is around 0.2, which corresponds –14 dB on the dB scale. The optimized values for the height and flare angle are close to 1.429 mm and 30°, respectively.

TABLE 2: RESULTS COMPARISON

	Height	**Flare angle**	$|S_{11}|$
Before optimization	2 mm	90°	0.645
After optimization	1.429 mm	30°	0.2

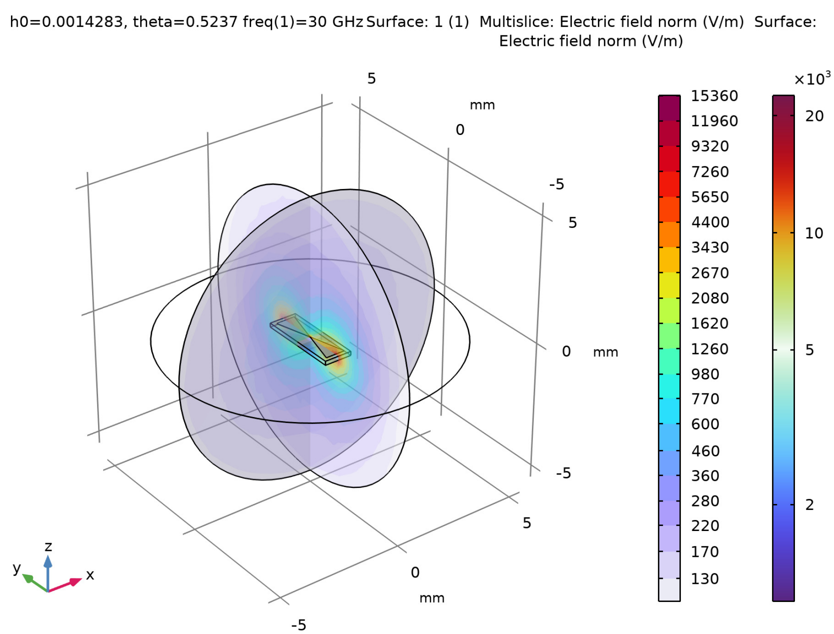


Figure 2: Logarithmic plot of the electric field norm after optimization.

The reliability analysis determines the probability that S_{11} is below −10 dB. The table titled Probability for Conditions in the Reliability Analysis group provides a value of approximately 0.89. This indicates that, under the given design parameter variations, there is about a 89% chance that S_{11} will be less than −10 dB, which is considered acceptable. The results suggests that, to achieve more robust performance of the printed antenna in the millimeter-wave range, high-precision etching is necessary rather than the conventional standard etching used for typical low-frequency printed circuit boards (PCBs).

Application Library path: `RF_Module/Antennas/bowtie_antenna_optimization`

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 **3D**.

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**
`f0`	`30[GHz]`	3E10 Hz	`Operating frequency`
`L0`	`c_const/f0`	0.0099931 m	`Free space wavelength`
`h0`	`2[mm]`	0.002 m	`Height of antenna arm`
`theta`	`90[deg]`	1.5708 rad	`Flare angle`
`Gap`	`L0/100`	9.9931E-5 m	`Gap at feed point`
`Padding`	`0.16[mm]`	1.6E-4 m	`Padding around antenna`
`Thickness`	`0.16[mm]`	1.6E-4 m	`Substrate thickness`

STUDY 1

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`.

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**.

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click  **Work Plane**.

2 In the **Settings** window for **Work Plane**, locate the **Unite Objects** section.

3 Clear the **Unite objects** checkbox.

Work Plane 1 (wp1) > Plane Geometry

In the **Model Builder** window, click **Plane Geometry**.

Work Plane 1 (wp1) > Square 1 (sq1)

1 In the **Work Plane** toolbar, click  **Square**.

2 In the **Settings** window for **Square**, locate the **Size** section.

3 In the **Side length** text field, type `L0`.

4 Locate the **Rotation Angle** section. In the **Rotation** text field, type `theta/2`.

Work Plane 1 (wp1) > Mirror 1 (mir1)

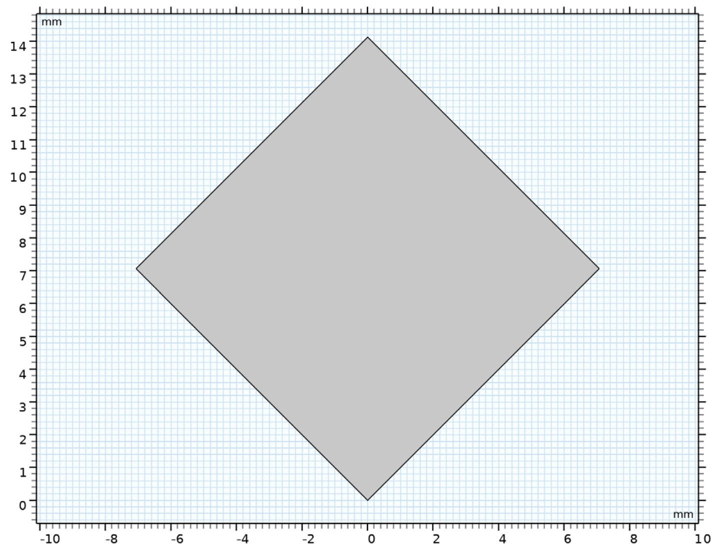
1 In the **Work Plane** toolbar, click **Transforms** and choose **Mirror**.

2 Select the object **sq1** only.

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

4 Select the **Keep input objects** checkbox.

5 Click **Build Selected**.



Work Plane 1 (wp1) > Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

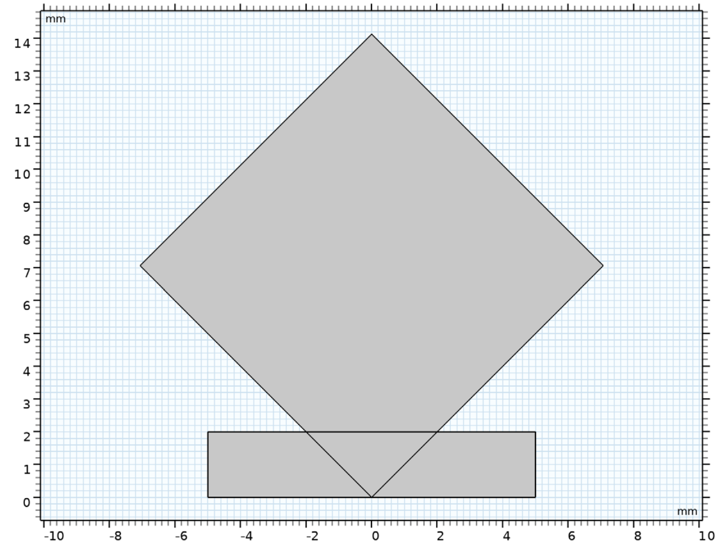
3 In the **Width** text field, type `L0`.

4 In the **Height** text field, type `h0`.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 In the **yw** text field, type `h0/2`.

7 Click **Build Selected**.



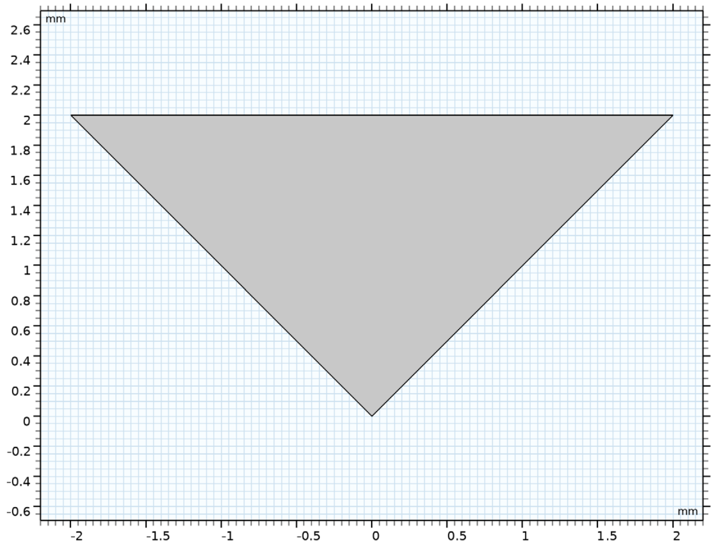
8 Click the **Zoom Extents** button in the **Graphics** toolbar.

Work Plane 1 (wp1) > Intersection 1 (int1)

1 In the **Work Plane** toolbar, click **Booleans and Partitions** and choose **Intersection**.

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

3 In the **Settings** window for **Intersection**, click **Build Selected**.



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

Work Plane 1 (wp1) > Mirror 2 (mir2)

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

2 Select the object **int1** only.

3 In the **Settings** window for **Mirror**, locate the **Normal Vector to Line of Reflection** section.

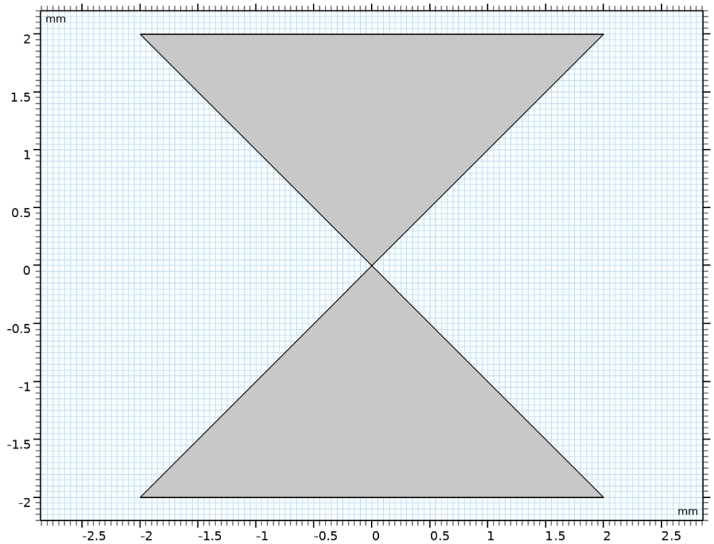
4 In the **xw** text field, type 0.

5 In the **yw** text field, type 1.

6 Locate the **Input** section. Select the **Keep input objects** checkbox.

7 Click **Build Selected**.

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



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

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

1 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 `tan(theta/2)*Gap`.

4 In the **Height** text field, type `Gap`.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

Work Plane 1 (wp1) > Rectangle 3 (r3)

1 In the **Work Plane** toolbar, click **Rectangle**.

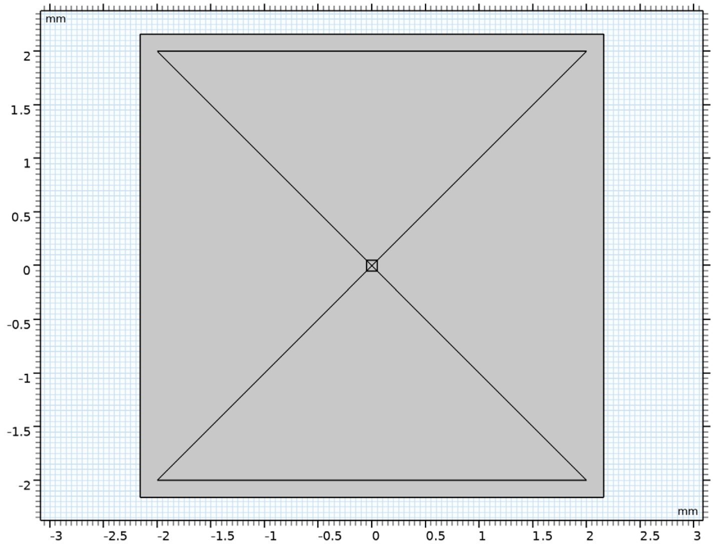
2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `2*h0*tan(theta/2)+2*Padding`.

4 In the **Height** text field, type `2*h0+2*Padding`.

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 Click **Build Selected**.



Extrude 1 (ext1)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Extrude**.

2 In the **Settings** window for **Extrude**, locate the **General** section.

3 Click the **Clear Selection** button for **Input objects**.

4 Select the object **wp1.r3** only.

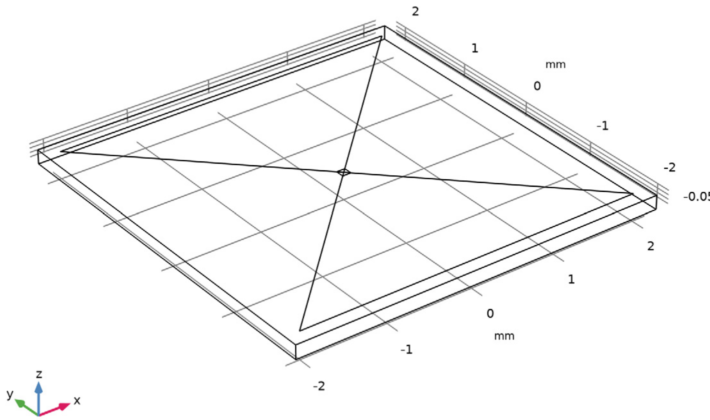
5 Locate the **Distances** section. In the table, enter the following settings:

Distances (mm)
Thickness

6 Select the **Reverse direction** checkbox.

7 Click **Build Selected**.

8 Click the **Wireframe Rendering** button in the **Graphics** toolbar.



Sphere 1 (sph1)

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

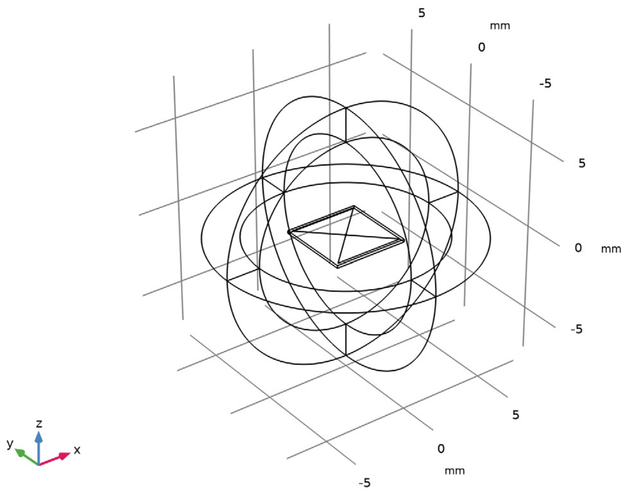
2 In the **Settings** window for **Sphere**, locate the **Size** section.

3 In the **Radius** text field, type `0.75*L0`.

4 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (mm)
Layer 1	L0/5

5 Click **Build All Objects**.

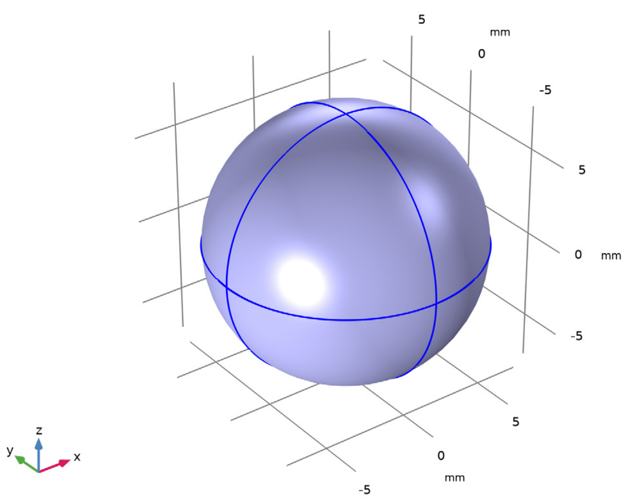


DEFINITIONS

Perfectly Matched Layer 1 (pml1)

1 In the **Definitions** toolbar, click **Perfectly Matched Layer**.

2 Select Domains 1–4 and 7–10 only.



3 In the **Settings** window for **Perfectly Matched Layer**, locate the **Geometry** section.

4 From the **Type** list, choose **Spherical**.

ADD MATERIAL FROM LIBRARY

In the **Home** toolbar, click **Windows** and choose **Add Material from Library**.

ADD MATERIAL

1 Go to the **Add Material** window.

2 In the tree, select **Built-in** > **Air**.

3 Click the **Add to Component** button in the window toolbar.

4 In the tree, select **Built-in** > **FR4 (Circuit Board)**.

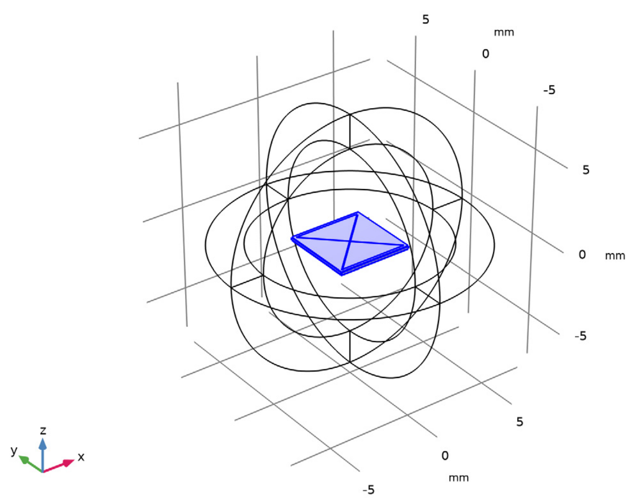
5 Click the **Add to Component** button in the window toolbar.

6 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

FR4 (Circuit Board) (mat2)

Select Domain 6 only.

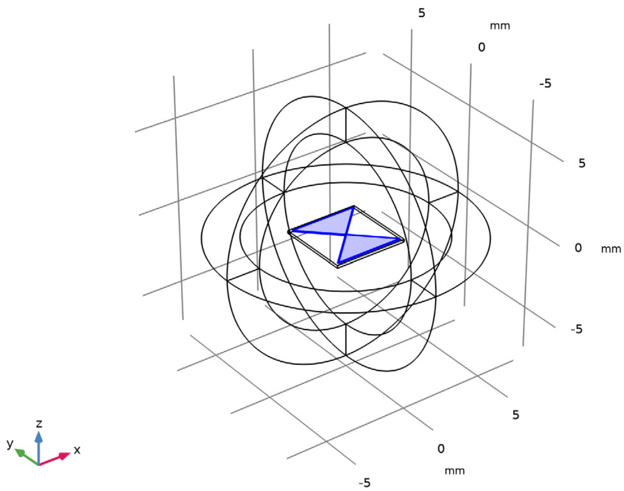


ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

Perfect Electric Conductor 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Perfect Electric Conductor**.

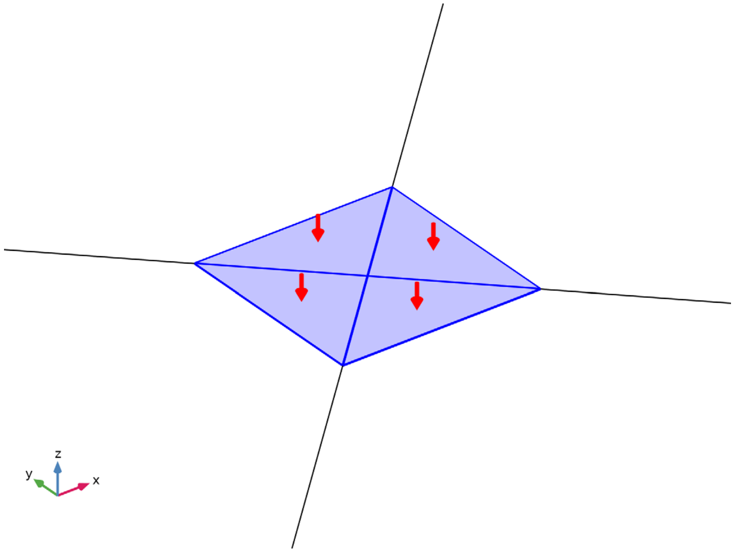
2 Select Boundaries 18 and 19 only.



Lumped Port 1

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

2 Select Boundaries 20–22 and 34 only.



Far-Field Domain 1

1 In the **Physics** toolbar, click **Domains** and choose **Far-Field Domain**.

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

DEFINITIONS

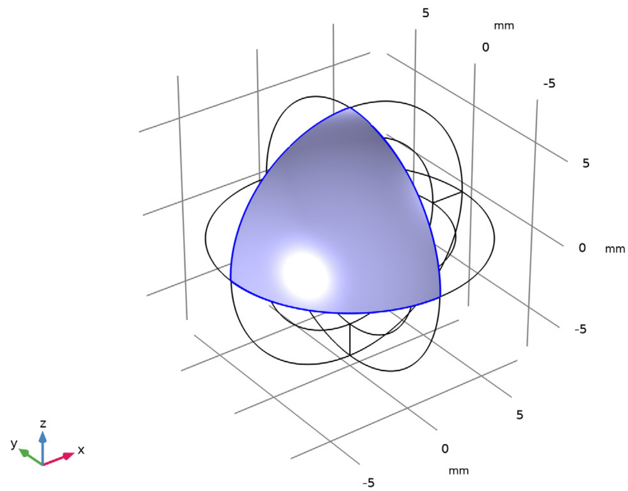
Hide for Physics 1

1 In the **Model Builder** window, right-click **View 1** and choose **Hide for Physics**.

2 In the **Settings** window for **Hide for Physics**, locate the **Geometric Entity Selection** section.

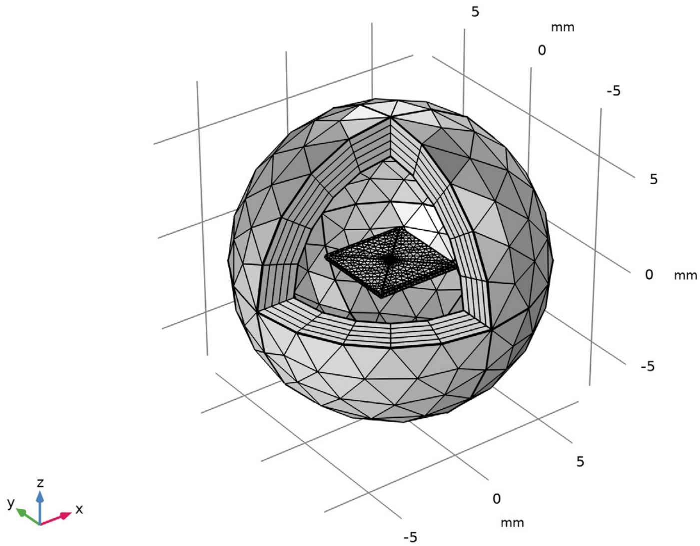
3 From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundaries 6 and 10 only.



MESH 1

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



2 Click the **Zoom In** button in the **Graphics** toolbar.

STUDY 1

Parameter Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Parameter Optimization**.

2 In the **Settings** window for **Parameter Optimization**, locate the **Optimization Solver** section.

3 From the **Method** list, choose **EGO**.

4 Click to expand the **Gaussian Process Function** section. Find the **Acquisition function settings** subsection. From the **Optimization method for acquisition function** list, choose **Monte Carlo**.

5 In the **Surrogate evaluations for optimization** text field, type `1e6`.

6 Locate the **Objective Function** section. In the table, enter the following settings:

Expression	Description	Evaluate for
abs(comp1.emw.S11)		Frequency Domain

7 Locate the **Control Parameters** section. Click + **Add** twice.

8 In the table, enter the following settings:

Parameter	Lower bound	Upper bound	Unit
h0 (Height of antenna arm)	0.8[mm]	2.5[mm]	m
theta (Flare angle)	30[deg]	90[deg]	rad

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

RESULTS

Multislice 1

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

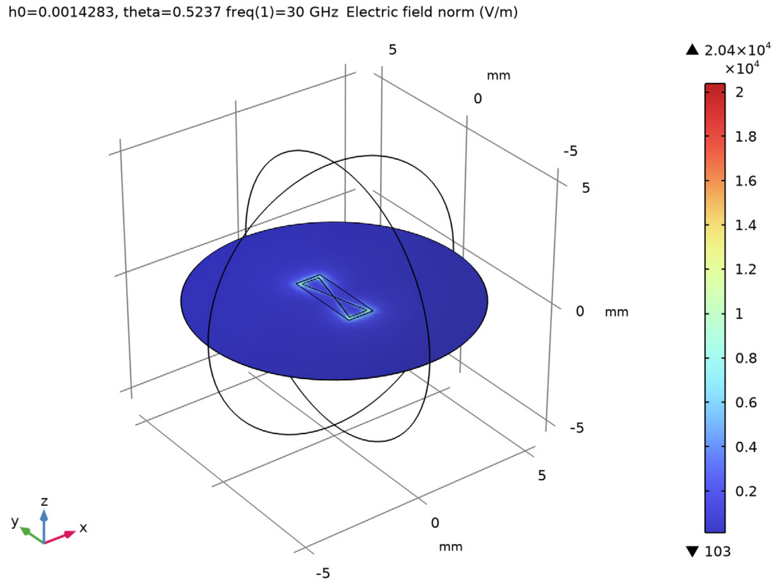
2 In the **Settings** window for **Multislice**, locate the **Multiplane Data** section.

3 Find the **X-planes** subsection. In the **Planes** text field, type 0.

4 Find the **Y-planes** subsection. In the **Planes** text field, type 0.

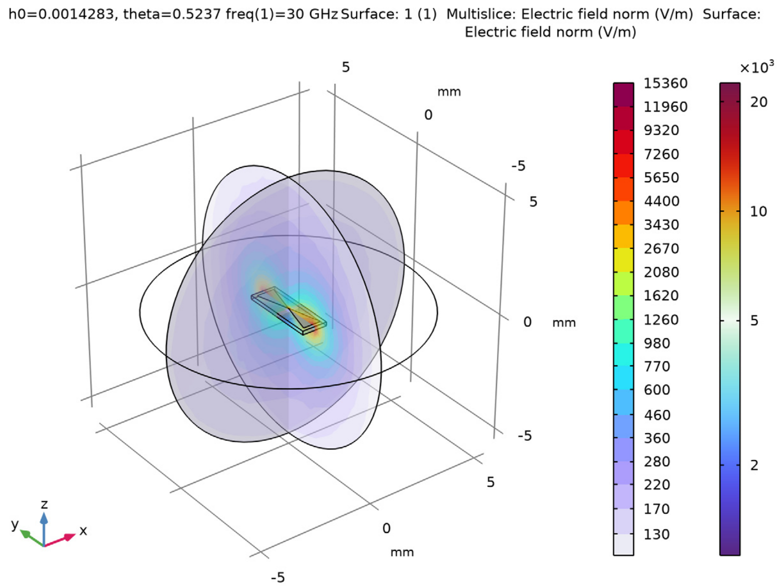
5 In the **Electric Field (emw)** toolbar, click **Plot**.

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



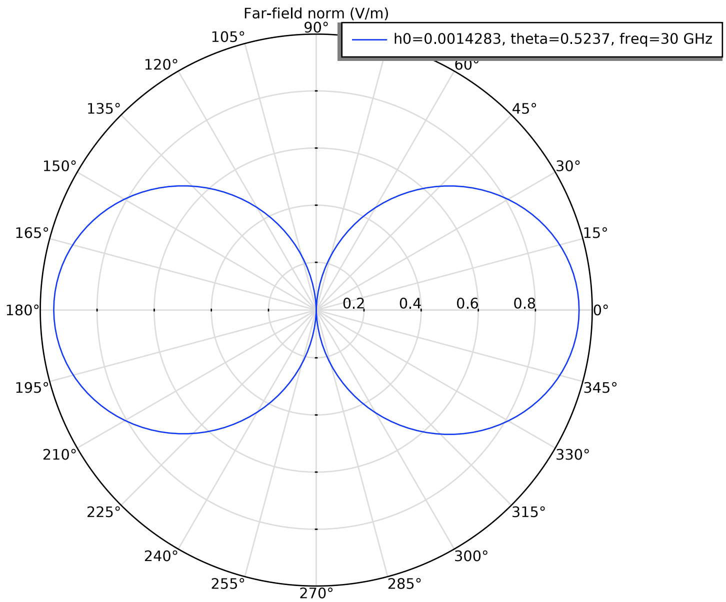
Electric Field, Logarithmic (emw)

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



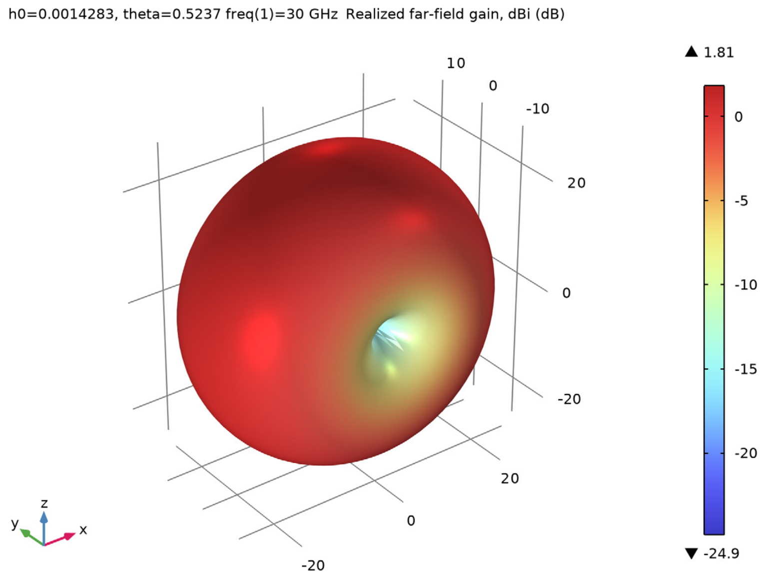
2D Far Field (emw)

In the **Model Builder** window, click **2D Far Field (emw)**.



3D Far Field, Gain (emw)

In the **Model Builder** window, click **3D Far Field, Gain (emw)**.



Global Evaluation 2

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
`h0`	`mm`	`Height of antenna arm`
`theta`	`rad`	`Flare angle`
`emw.Zport_1`	Ω	`Lumped port 1 impedance`
`abs(emw.S11)`	`1`	`Reflection coefficient`

4 Click **Evaluate**.

The **Gaussian Process 1** surrogate model used for the EGO can be reused to conduct a reliability analysis as part of uncertainty quantification with design parameter variations.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Frequency Domain**.

4 Click the **Add Study** button in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Frequency Domain

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

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

3 In the **Model Builder** window, click **Study 2**.

4 In the **Settings** window for **Study**, locate the **Study Settings** section.

5 Clear the **Generate default plots** checkbox.

Uncertainty Quantification

1 In the **Study** toolbar, click **More Study Extensions** and choose **Uncertainty Quantification**.

2 In the **Settings** window for **Uncertainty Quantification**, locate the **Uncertainty Quantification Settings** section.

3 From the **UQ study type** list, choose **Reliability analysis, EGRA**.

4 Find the **Surrogate model settings** subsection. From the **Gaussian process function** list, choose **Gaussian Process 1 (gpm1_1)**.

5 From the **Compute action** list, choose **Improve and analyze**.

6 Locate the **Quantities of Interest** section. Click **Add**.

7 In the table, enter the following settings:

Function name	Expression	Include study-dependent input	True if	Threshold
`Reflection`	`abs(comp1.emw.S11)`	Reduce to single global output	Smaller than threshold	`10^(-10/20)`

The given threshold expression will calculate the probability that S_{11} will fall below -10 dB.

8 Locate the **Input Parameters** section. Click **Add**.

9 In the table, enter the following settings:

Parameter	Source type	Source description
h0 (Height of antenna arm)	Analytic	Uniform

10 In the table, click to select the cell at row number 1 and column number 3.

11 From the **Distribution** list, choose **Normal(μ,σ)**.

12 In the **Mean** text field, type `1.4295[mm]`.

Use the optimized value of the height `h0` for the **Mean**.

13 In the **Standard deviation** text field, type `1.4295*0.045[mm]`.

The standard deviation is defined as above to ensure 2σ is close to the non-high-precision etching tolerance of 0.127 mm.

14 From the **CDF-Lower** list, choose **Manual**.

15 In the **Lower bound** text field, type `1.4295[mm]-2*1.4295[mm]*0.045`.

16 From the **CDF-Upper** list, choose **Manual**.

17 In the **Upper bound** text field, type `1.4295[mm]+2*1.4295[mm]*0.045`.

The range specified by `h0`±2σ will cover approximately 95.45% of the variations.

18 Click **Add**.

19 In the table, enter the following settings:

Parameter	Source type	Source description
theta (Flare angle)	Analytic	Uniform

20 In the table, click to select the cell at row number 2 and column number 3.

21 From the **Distribution** list, choose **Normal(μ,σ)**.

22 In the **Mean** text field, type `30[deg]`.

23 In the **Standard deviation** text field, type `30[deg]*0.045`.

24 From the **CDF-Lower** list, choose **Manual**.

25 In the **Lower bound** text field, type `30[deg]-2*30[deg]*0.045`.

26 From the **CDF-Upper** list, choose **Manual**.

27 In the **Upper bound** text field, type `30[deg]+2*30[deg]*0.045`.

28 Locate the **Surrogate-Based Response Surface** section. In the table, enter the following settings:

Parameter	Point generation method	Distribution resolution	Parameter value list
h0	Distribution	100	
theta	Distribution	100	

Uncertainty Quantification 1

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

RESULTS

In the **Model Builder** window, expand the **Results** > **Tables** node.

Table 5

The **Probability for Conditions** table under the **Reliability Analysis 1** group shows a value of approximately 0.89. This implies that, under the given conditions — representing a non-high-precision PCB etching tolerance — there is roughly a 89% chance that S_{11} will fall below -10 dB.