Created in COMSOL Multiphysics 6.0

Integrated Square-Shaped Spiral Inductor

Introduction

This example presents a model of a microscale square inductor, used for LC bandpass filters in microelectromechanical systems (MEMS).

The purpose of the application is to calculate the self-inductance of the microinductor. Given the magnetic field, you can compute the self-inductance, L, from the relation

$$L = \frac{2W_m}{I^2}$$

where W_m is the magnetic energy and I is the current. The application uses the Terminal boundary condition, which sets the current to 1 A and automatically computes the self-inductance. The self-inductance L becomes available as the L_{11} component of the inductance matrix.

Model Definition

The model geometry consists of the spiral-shaped inductor and the air surrounding it. Figure 1 below shows the inductor and air domains used in the model. The outer dimensions of the model geometry are around 0.3 mm.

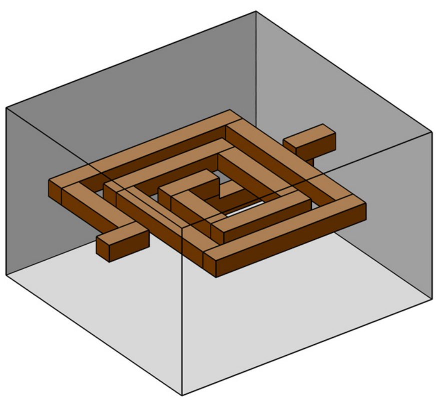

Figure 1: Inductor geometry and the surrounding air.

The model equations are the following:

$$-\nabla \cdot (\sigma \nabla V - \mathbf{J}_\mathrm{e}) = 0$$

$$\nabla \times (\mu_0^{-1} \mu_\mathrm{r}^{-1} \nabla \times \mathbf{A}) + \sigma \nabla V = \mathbf{J}_\mathrm{e}$$

In the equations above, σ denotes the electrical conductivity, $\mathbf{A}$ the magnetic vector potential, V the electric scalar potential, $\mathbf{J}_e$ the externally generated current density vector, μ_0 the permittivity in vacuum, and μ_r the relative permeability.

The electrical conductivity in the coil is set to 10^6 S/m and 1 S/m in air. The conductivity of air is arbitrarily set to a small value in order to avoid singularities in the model, but the error becomes small as long as the value of the conductivity is small compared with the other conductivities in the model.

The constitutive relation is specified with the expression

$$\mathbf{B} = \mu_0\mu_r\mathbf{H}$$

where $\mathbf{H}$ denotes the magnetic field.

The boundary conditions are of three different types corresponding to the three different boundary groups; see Figure 2 (a), (b), and (c).

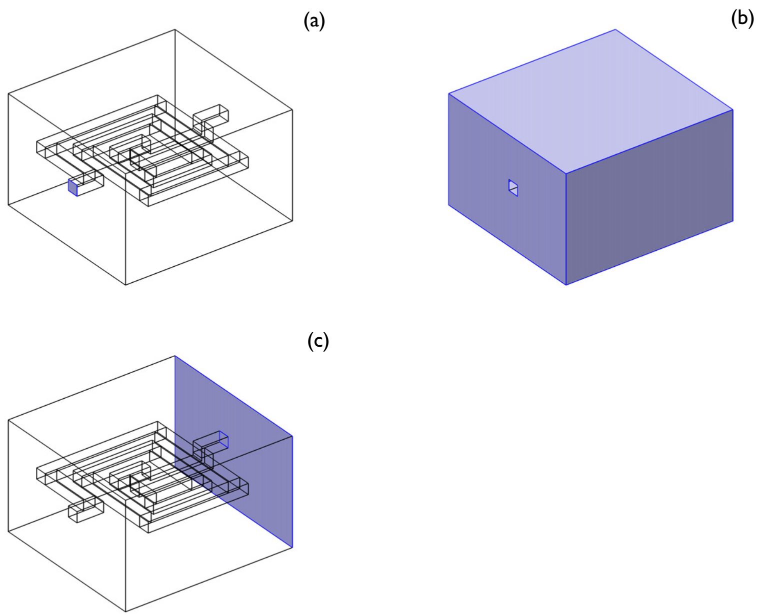

Figure 2: Boundaries with the same type of boundary conditions.

The boundary condition for the boundary highlighted in Figure 2 (a) is a magnetic insulation boundary with a terminal boundary condition. For the boundaries in Figure 2 (b), both magnetic and electric insulation prevail. The condition for the last boundary, Figure 2 (c), is magnetic insulation set to a constant electric potential of 0 V (ground).

Results

Figure 3 shows the electric potential in the inductor and the magnetic flux lines. The color of the flow lines represents the magnitude of the magnetic flux. As expected this flux is largest in the middle of the inductor.

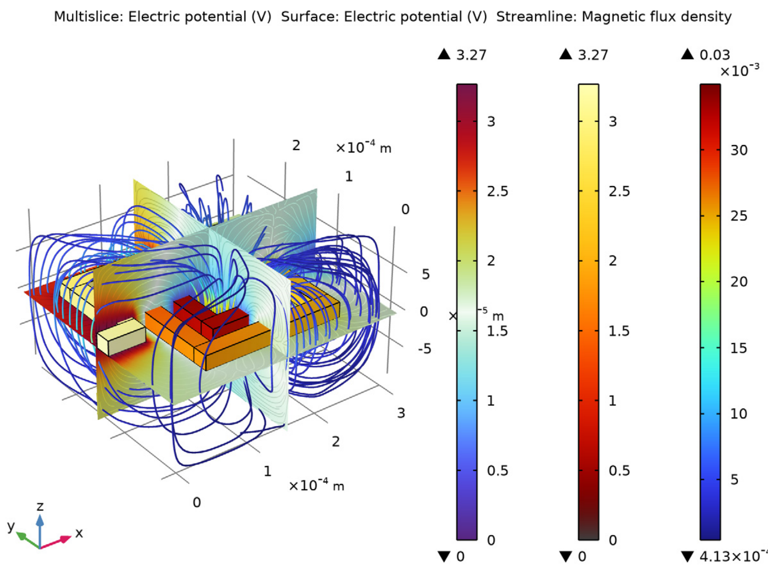

Figure 3: Electric potential in the device and magnetic flux lines around the device.

The computed self-inductance is 0.75 nH.

Application Library path: `ACDC_Module/Inductive_Devices_and_Coils/spiral_inductor`

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 **AC/DC>Electromagnetic Fields>Vector Formulations>Magnetic and Electric Fields (mef)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Stationary**.
6 Click **Done**.

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 `spiral_inductor.mphbin`.
5 Click **Import**.
6 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

   This geometry would be relatively straightforward to create from scratch; here it is imported for convenience.

MATERIALS

Conductor

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
2 Right-click **Material 1 (mat1)** and choose **Rename**.
3 In the **Rename Material** dialog box, type `Conductor` in the **New label** text field.
4 Click **OK**.
5 Select Domain 2 only.
6 In the **Settings** window for **Material**, locate the **Material Contents** section.

7 In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	1e6	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

Air

1 In the **Model Builder** window, right-click **Materials** and choose **Blank Material**.

2 Right-click **Material 2 (mat2)** and choose **Rename**.

3 In the **Rename Material** dialog box, type `Air` in the **New label** text field.

4 Click **OK**.

5 Select Domain 1 only.

6 In the **Settings** window for **Material**, locate the **Material Contents** section.

7 In the table, enter the following settings:

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

Setting the conductivity to zero in the air would lead to a numerically singular problem. You can avoid this problem by using a small nonzero value. As 1 S/m is much less than the electric conductivity in the inductor, the fields will only be marginally affected.

MAGNETIC AND ELECTRIC FIELDS (MEF)

Magnetic Insulation 1

In the **Model Builder** window, under **Component 1 (comp1)> Magnetic and Electric Fields (mef)** click **Magnetic Insulation 1**.

Terminal 1

1 In the **Physics** toolbar, click **Attributes** and choose **Terminal**.

2 Select Boundary 5 only.

3 In the **Settings** window for **Terminal**, locate the **Terminal** section.

4 In the I_0 text field, type 1.

Magnetic Insulation 1

In the **Model Builder** window, click **Magnetic Insulation 1**.

Ground 1

1 In the **Physics** toolbar, click **Attributes** and choose **Ground**.

2 Select Boundary 76 only.

This concludes the boundary settings. Note that the boundaries that you have not assigned are electrically and magnetically insulated by default.

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 From the **Element size** list, choose **Coarser**.

4 In the **Home** toolbar, click **Build Mesh**.

STUDY 1

Click **Compute**.

RESULTS

Magnetic Flux Density Norm (mef)

The default plot shows the electric potential distribution in three cross-sections. There are plenty of other ways of visualizing the solution. The following instructions detail how to combine an electric potential distribution plot on the surface of the inductor with a streamline plot of the magnetic flux density in the air surrounding it.

3D Plot Group 3

In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

Surface 1

1 In the **Model Builder** window, right-click **Electric Potential (mef)** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Coloring and Style** section.

3 From the **Color table** list, choose **GrayBody**.

Study 1/Solution 1 (sol1)

In the **Model Builder** window, expand the **Results>Datasets** node, then click **Study 1/ Solution 1 (sol1)**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

Selecting the boundaries of the inductor is most effectively done by first selecting all boundaries, then removing the exterior boundaries of the air box from the selection.

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

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

4 From the **Selection** list, choose **All boundaries**.

5 Select Boundaries 5–9, 11–74, and 76 only.

Streamline 1

1 In the **Model Builder** window, right-click **Electric Potential (mef)** and choose **Streamline**.

2 In the **Settings** window for **Streamline**, locate the **Streamline Positioning** section.

3 From the **Positioning** list, choose **Starting-point controlled**.

4 In the **Points** text field, type 3.

5 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Type** list, choose **Tube**.

6 In the **Tube radius expression** text field, type 1e-6.

7 Select the **Radius scale factor** check box.

8 Click to expand the **Quality** section. From the **Resolution** list, choose **Finer**.

9 In the **Electric Potential (mef)** toolbar, click **Plot**.

The **Magnetic Insulation** condition on the exterior boundaries causes the field lines to bend and follow the contours of the box. This inevitably introduces a systematic error to the inductance computation. It would be possible to reduce this error by increasing the size of the box, or introducing an infinite element domain. Nevertheless, since the field is comparatively small near the surface of the box, the result is reasonably accurate already. Try visualizing the local magnitude of the field by having it decide the color of the streamlines.

Color Expression 1

1 Right-click **Streamline 1** and choose **Color Expression**.

2 In the **Settings** window for **Color Expression**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Magnetic and Electric Fields>Magnetic>mef.normB - Magnetic flux density norm - T**.

Streamline 1

1 In the **Model Builder** window, click **Streamline 1**.

2 In the **Electric Potential (mef)** toolbar, click **Plot**.

Global Evaluation 1

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

2 In the **Settings** window for **Global Evaluation**, click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Magnetic and Electric Fields>Terminals>mef.L11 - Inductance - H**.

3 Click **Evaluate**.

TABLE

1 Go to the **Table** window.

The inductance evaluates to 0.75 nH.